Basic Industrial Electric
ELECTRICAL

In industrial maintenance mechanic or electrician may have a machine controller or an electrical device that needs to be changed out or sent out for repair. This is when you will be referring to the OEM manual for guidance. In the following chapter there will be terminology and definitions that you will see in these manuals. Most controllers have just a few parameters that need to be set where others are more complicated and need formals and specifications entered. The more you are exposed to these devices the more you will see that they all have common parameters from one controller to the next. Listed here are just a few of the most common parameters. Ramps, RPM, Set Point, Baud Rate, Integral, Deflection, Amps, Volts, Torque, and Current Limit. On a motor controller you always have to enter all specifications on motor name plates. On a temperature controller you will always have to set the parameter of what thermal couple you are using to since temperature. On a counter you will always have to set per feet, per inch, or per mm. So when reading this chapter don't take it as just a bunch of junk. You will need this information in your day to day career as a maintenance technician.

 Basic Machine Electric
A simple machine start stop circuit will look like the drawing in (figure 1) below.
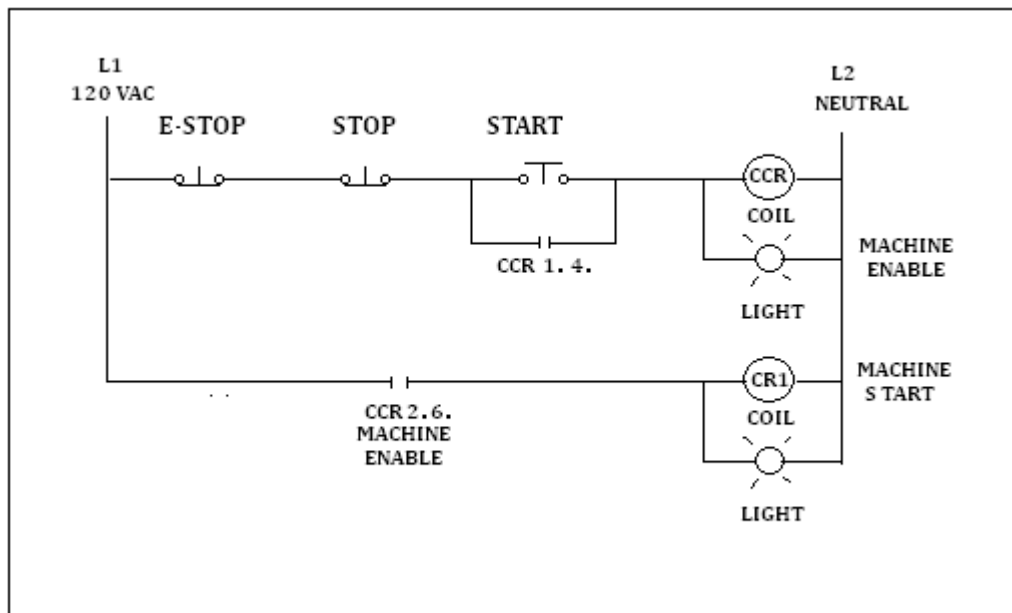

   Figure 1
This drawing in figure 1 is showing an E-stop switch at the beginning of the machine control power, inline with a machine stop switch. Why have two stop switches? E-stop switches are designed for a emergency stop situation. It has a larger knob (2" or2 ½") so it is easy to locate and push. The machine stop is a regular 30MM are a 22MM and is only for the machine stop under normal conditions.
As we look at the drawing in figure 1. we go to the start button. Normally open contacts and in this case momentary. This means the contacts will only be close

as long as the button is held closed. So when we let go the contacts open and the circuit is broke. This is why you will see a open contact underneath of the start button. This open contact which is a (Latch) is two contacts on relay CCR which is energized when we push the start button, and closes the contacts on terminals 1. and 4. which holds the circuit closed until the stop button breaks the circuit. Also shown in the drawing figure 1 is a relay marked CR1. This relay is the main control relay that runs the machine. Relay CR1 cannot be energized until CCR relay is energized. Contacts 2 and 6 are closed. On older machine 120 Volts AC was a common machine control voltage. With newer machine and PLCs and Machine controls being operated by computers. The Voltage vary from 5 VDC to 30 VDC Not too many machine are using the 120 VAC voltage because of noise and other problems with new computerized controls being so sensitive. The most common machine control voltage now is 24 volts VAC and VDC. These voltages are good because most devices are designed for devices requiring 0-32 volts.

Most electrical repairs on machines usually require a trained industrial electrician. But on a day to day cycle in production. A maintenance technician (mechanic) may be confronted with an electrical problem on a machine. Some manufacturing plants don't have an electrician on staff, only maintenance mechanics that know machine electric.

The most common electric problem on production machines is the E-stop circuit is open. There are many reasons for the E-stop circuit to be open. First would be if any E-stop buttons are pushed in. With new safety standards there are several e-stops on just about any machine. After making sure these are in the out position, look at limits and sensors. Most all machine guards that can be opened by the operator will have some type of limit or sensor to open the E-stop circuit if guard is open. These can be magnet contact switches, proximity, or limit switch. The next devices that may be in a E-stop circuit may be flow control valves, pressure valves, temperature thermo couples, and other devices that want let a machine start until these controls see a certain input that will give the machine an enable signal.

With a good volt meter this circuit can be checked on the machine terminal strip inside control panel and detect where the circuit is open.
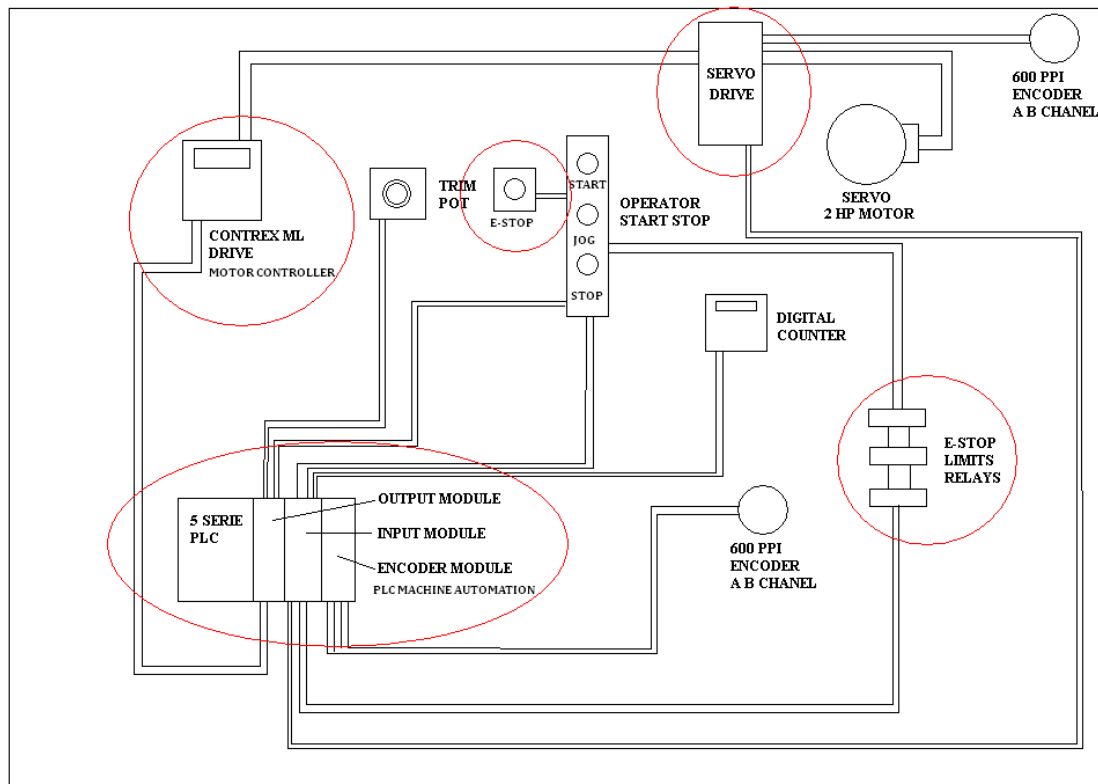
FIGURE 2
In (Figure 2.) you can see red circles showing where the E-stop circuit is associated with different devices and switches. This is a small rotating production machine. There is three (3) limit switches, one E-stop switch, normally close contacts on the PLC, normally closed contacts on motor controller and normally closed contacts on the servo controller. Now how do we know from this picture that these close contact exist. We don't but we have the manuals and the manuals show this. You ask where did the manuals come from. This brings up the next part of checking the E-stop circuit. You have to know the complete E-stop circuit in order to know if you have a completed circuit. Most E-stop circuits hold a relay or input to a PLC that if the circuit is complete will close contacts giving you the control voltage to machine controls to be enabled. See figure 2 below.
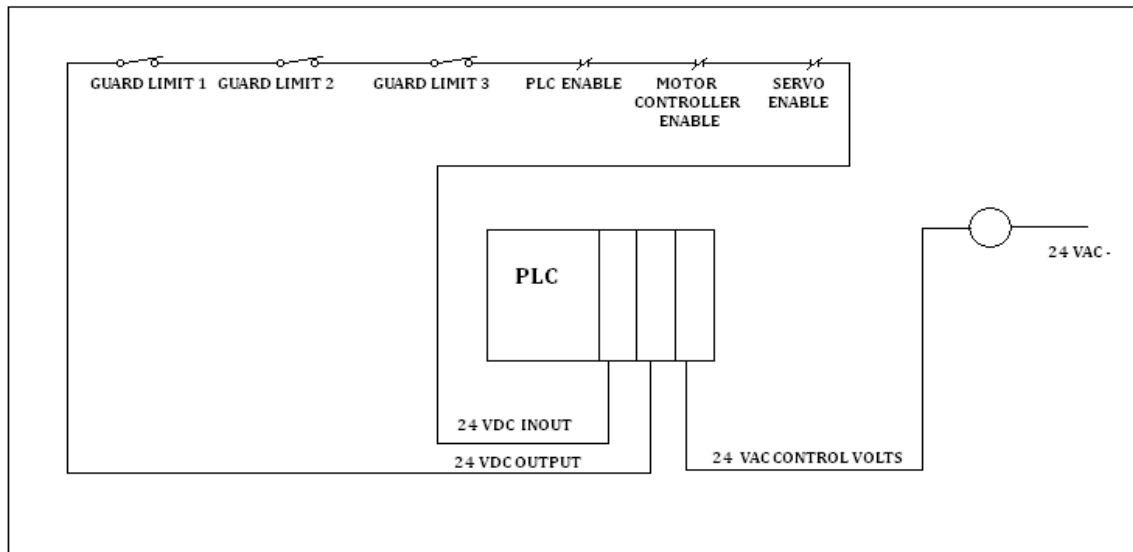
E STOP BUTTON

Figure 3.
In the drawing (figure 3) you can see there are a total of six things that can keep this machine from being enabled. If any of the contacts are open this machine want run. This is one example on a small scale. Large production lines and machines may have as many as 50 relays and contacts that have to be checked. This may seem like this will take for ever to check all these relays and contacts. Not if you go to the terminal block where they are wired in the control panel and start checking your output from one device to the next to see where the circuit is broken. If you are working on newer equipment and have a schematic, this should only take several minutes. If your working on older equipment and don't have a schematic, this is a good time to make one. You will need to have a E-stop circuit schematic eventually, so you might as well make one as soon as possible. This is one electrical problem that you will see over and over again. There is always going to be a guard open, or a limit switch open and you will have be able to troubleshoot this problem as quickly as possible.

To continue with the basics of machine electric and controls, it will very important to learn how to use a volt meter or multimeter. This meter is used daily by anyone in the industrial maintenance field.

Checking voltage, amps, DC volts, Ohms and Infinite are signals that things that will become everyday commonly used readings. To check for a blown fuse you will check voltage on fuses. Once a fuse is pulled you put your meter on Infinite and place the two leads on each end of fuse, if the fuse is good your meter will beep and show 0.0 on display. If fuse is bad your meter will stay on default setting on meter and you will not get a beep. Having faith in your meter is something you must know. If meter is giving false readings are you are not sure about the readings, always double check with another meter. Always make sure you are wearing the proper PPE when working around electric.

Tag Out/Lock Out!!!

Power off machine. Turn off breaker or disconnect. Use tag out or lock out on main power. Never work in a condition where this is not applied. No exception!

Multimeter

A digital multimeter

A multimeter or a multitester, also known as a VOM (Volt-Ohm meter), is an electronic measuring instrument that combines several measurement functions in one unit. A typical multimeter may include features such as the ability to measure voltage, current and resistance. Multimeters may use analog or digital circuits— analog multimeters (AMM) and digital multimeters (often abbreviated DMM or DVOM.) Analog instruments are usually based on a microammeter whose pointer moves over a scale calibrated for all the different measurements that can be

made; digital instruments usually display digits, but may display a bar of a length proportional to the quantity being measured.

A multimeter can be a hand-held device useful for basic <u>fault</u> finding and field service work or a <u>bench instrument</u> which can measure to a very high degree of accuracy. They can be used to troubleshoot electrical problems in a wide array of industrial and household devices such as <u>electronic equipment</u>, motor controls, <u>domestic appliances</u>, <u>power supplies</u>, and wiring systems.

Multimeters are available in a wide range of features and prices. Cheap multimeters can cost less than US$10, while the top of the line multimeters can cost more than US$5,000.

Operation

A multimeter is a combination of a multirange DC voltmeter, multirange AC voltmeter, multirange ammeter, and multirange ohmmeter. An un-amplified analog multimeter combines a meter movement, range resistors and switches.

For an analog meter movement, DC voltage is measured with a series resistor connected between the meter movement and the circuit under test. A set of switches allows greater resistance to be inserted for higher voltage ranges. The product of the basic full-scale deflection current of the movement, and the sum of the series resistance and the movement's own resistance, gives the full-scale voltage of the range. As an example, a meter movement that required 1 milliamp for full scale deflection, with an internal resistance of 500 ohms, would, on a 10-volt range of the multimeter, have 9,500 ohms of series resistance. For analog current ranges, low-resistance shunts are connected in parallel with the meter movement to divert most of the current around the coil. Again for the case of a hypothetical 1 mA, 500 ohm movement on a 1 Ampere range, the shunt resistance would be just over 0.5 ohms.

Moving coil instruments respond only to the average value of the current through them. To measure alternating current, a <u>rectifier</u> diode is inserted in the circuit so that the average value of current is non-zero. Since the average value and the root-mean-square value of a waveform need not be the same, simple rectifier-type circuits may only be accurate for sinusoidal waveforms. Other wave shapes require a different calibration factor to relate RMS and average value. Since practical rectifiers have non-zero voltage drop, accuracy and sensitivity is poor at low values.

To measure resistance, a small dry cell within the instrument passes a current through the device under test and the meter coil. Since the current available depends on the state of charge of the dry cell, a multimeter usually has an adjustment for the ohms scale to zero it. In the usual circuit found in analog multimeters, the meter deflection is inversely proportional to the resistance; so

full-scale is 0 ohms, and high resistance corresponds to smaller deflections. The ohms scale is compressed, so resolution is better at lower resistance values.

Amplified instruments simplify the design of the series and shunt resistor networks. The internal resistance of the coil is decoupled from the selection of the series and shunt range resistors; the series network becomes a <u>voltage divider</u>. Where AC measurements are required, the rectifier can be placed after the amplifier stage, improving precision at low range.

Digital instruments, which necessarily incorporate amplifiers, use the same principles as analog instruments for range resistors. For resistance measurements, usually a small constant current is passed through the device under test and the digital multimeter reads the resultant voltage drop; this eliminates the scale compression found in analog meters, but requires a source of significant current. An autoranging digital multimeter can automatically adjust the scaling network so that the measurement uses the full precision of the A/D converter.

In all types of multimeters, the quality of the switching elements is critical to stable and accurate measurements. Stability of the resistors is a limiting factor in the long-term accuracy and precision of the instrument.

Quantities measured

Contemporary multimeters can measure many quantities. The common ones are:

- <u>Voltage</u>, <u>alternating</u> and <u>direct</u>, in <u>volts</u>.
- <u>Current</u>, alternating and direct, in <u>amperes</u>.
  The <u>frequency</u> range for which AC measurements are accurate must be specified.
- <u>Resistance</u> in <u>ohms</u>.

Additionally, some multimeters measure:

- <u>Capacitance</u> in <u>farads</u>.
- <u>Conductance</u> in <u>siemens</u>.
- <u>Decibels</u>.
- <u>Duty cycle</u> as a <u>percentage</u>.
- <u>Frequency</u> in <u>hertz</u>.
- <u>Inductance</u> in <u>henrys</u>.
- <u>Temperature</u> in degrees <u>Celsius</u> or <u>Fahrenheit</u>, with an appropriate temperature <u>test probe</u>, often a <u>thermocouple</u>.

Digital multimeters may also include circuits for:

- <u>Continuity tester</u>; sounds when a circuit conducts

- Diodes (measuring forward drop of diode junctions), and transistors (measuring current gain and other parameters)
- Battery checking for simple 1.5 volt and 9 volt batteries. This is a current loaded voltage scale which simulates in-use voltage measurement.

Various sensors can be attached to multimeters to take measurements such as:

- Light level
- Acidity/Alkalinity(pH)
- Wind speed
- Relative humidity

Resolution

Resolution and accuracy

The resolution of a multimeter is the smallest part of the scale which can be shown. The resolution is scale dependent. On some digital multimeters it can be configured, with higher resolution measurements taking longer to complete. For example, a multimeter that has a 1mV resolution on a 10V scale can show changes in measurements in 1mV increments.

Absolute accuracy is the error of the measurement compared to a perfect measurement. Relative accuracy is the error of the measurement compared to the device used to calibrate the multimeter. Most multimeter datasheets provide relative accuracy. To compute the absolute accuracy from the relative accuracy of a multimeter add the absolute accuracy of the device used to calibrate the multimeter to the relative accuracy of the multimeter.

Digital

The resolution of a multimeter is often specified in the number of decimal digits resolved and displayed. If the most significant digit cannot take all values from 0 to 9 is often termed a fractional digit. For example, a multimeter which can read up to 19999 (plus an embedded decimal point) is said to read 4½ digits.

By convention, if the most significant digit can be either 0 or 1, it is termed a half-digit; if it can take higher values without reaching 9 (often 3 or 5), it may be called three-quarters of a digit. A 5½ digit multimeter would display one "half digit" that could only display 0 or 1, followed by five digits taking all values from 0 to 9. Such a meter could show positive or negative values from 0 to 199,999. A 3¾ digit meter can display a quantity from 0 to 3,999 or 5,999, depending on the manufacturer.

While a digital display can easily be extended in precision, the extra digits are of no value if not accompanied by care in the design and calibration of the analog

portions of the multimeter. Meaningful high-resolution measurements require a good understanding of the instrument specifications, good control of the measurement conditions, and traceability of the calibration of the instrument. However, even if its resolution exceeds the accuracy, a meter can be useful for comparing measurements. For example, a meter reading 5½ stable digits may indicate that one nominally 100,000 ohm resistor is about 7 ohms greater than another, although the error of each measurement is 0.2% of reading plus 0.05% of full-scale value.

Specifying "display counts" is another way to specify the resolution. Display counts give the largest number, or the largest number plus one (so the count number looks nicer) the multimeter's display can show, ignoring a decimal separator. For example, a 5½ digit multimeter can also be specified as a 199999 display count or 200000 display count multimeter. Often the display count is just called the count in multimeter specifications.

Analog

Display face of an analog multimeter

Resolution of analog multimeters is limited by the width of the scale pointer, parallax, vibration of the pointer, the accuracy of printing of scales, zero calibration, number of ranges, and errors due to non-horizontal use of the mechanical display. Accuracy of readings obtained is also often compromised by miscounting division markings, errors in mental arithmetic, parallax observation errors, and less than perfect eyesight. Mirrored scales and larger meter movements are used to improve resolution; two and a half to three digits equivalent resolution is usual (and is usually adequate for the limited precision needed for most measurements).

Resistance measurements, in particular, are of low precision due to the typical resistance measurement circuit which compresses the scale heavily at the higher resistance values. Inexpensive analog meters may have only a single resistance scale, seriously restricting the range of precise measurements. Typically an analog meter will have a panel adjustment to set the zero-ohms calibration of the meter, to compensate for the varying voltage of the meter battery.

Accuracy

Digital multimeters generally take measurements with accuracy superior to their analog counterparts. Standard analog multimeters measure with typically ±3% accuracy, though instruments of higher accuracy are made. Standard portable digital multimeters are specified to have an accuracy of typically 0.5% on the DC voltage ranges. Mainstream bench-top multimeters are available with specified accuracy of better than ±0.01%. Laboratory grade instruments can have accuracies of a few parts per million.

Accuracy figures need to be interpreted with care. The accuracy of an analog instrument usually refers to full-scale deflection; a measurement of 30V on the 100V scale of a 3% meter is subject to an error of 3V, 10% of the reading. Digital meters usually specify accuracy as a percentage of reading plus a percentage of full-scale value, sometimes expressed in counts rather than percentage terms.

Quoted accuracy is specified as being that of the lower millivolt (mV) DC range, and is known as the "basic DC volts accuracy" figure. Higher DC voltage ranges, current, resistance, AC and other ranges will usually have a lower accuracy than the basic DC volts figure. AC measurements only meet specified accuracy within a specified range of frequencies.

Manufacturers can provide calibration services so that new meters may be purchased with a certificate of calibration indicating the meter has been adjusted to standards traceable to, for example, the US National Institute of Standards and Technology (NIST), or other national standards organization.

Test equipment tends to drift out of calibration over time, and the specified accuracy cannot be relied upon indefinitely. For more expensive equipment, manufacturers and third parties provide calibration services so that older equipment may be recalibrated and recertified. The cost of such services is disproportionate for inexpensive equipment; however extreme accuracy is not required for most routine testing. Multimeters used for critical measurements may be part of a metrology program to assure calibration.

Some instrument assume sine waveform for measurements but for distorted wave forms a true RMS converter (TrueRMS) may be needed for correct RMS calculation.

Sensitivity and input impedance

When used for measuring voltage, the input impedance of the multimeter must be very high compared to the impedance of the circuit being measured; otherwise circuit operation may be changed, and the reading will also be inaccurate.

Meters with electronic amplifiers (all digital multimeters and some analog meters) have a fixed input impedance that is high enough not to disturb most circuits. This is often either one or ten megohms; the standardization of the input resistance allows the use of external high-resistance probes which form a voltage divider with the input resistance to extend voltage range up to tens of thousands of volts. High-end multimeters generally provide an input impedance >10 Gigaohms for ranges less than or equal to 10V. Some high-end multimeters provide >10 Gigaohms of impedance to ranges greater than 10V.

Most analog multimeters of the moving-pointer type are unbuffered, and draw current from the circuit under test to deflect the meter pointer. The impedance of the meter varies depending on the basic sensitivity of the meter movement and the range which is selected. For example, a meter with a typical 20,000 ohms/volt sensitivity will have an input resistance of two million ohms on the 100 volt range (100 V * 20,000 ohms/volt = 2,000,000 ohms). On every range, at full scale voltage of the range, the full current required to deflect the meter movement is taken from the circuit under test. Lower sensitivity meter movements are acceptable for testing in circuits where source impedances are low compared to the meter impedance, for example, power circuits; these meters are more rugged mechanically. Some measurements in signal circuits require higher sensitivity movements so as not to load the circuit under test with the meter impedance.

Sometimes sensitivity is confused with resolution of a meter, which is defined as the lowest voltage, current or resistance change that can change the observed reading

For general-purpose digital multimeters, the lowest voltage range is typically several hundred millivolts AC or DC, but the lowest current range may be several hundred milliamperes, although instruments with greater current sensitivity are available. Measurement of low resistance requires lead resistance (measured by touching the test probes together) to be subtracted for best accuracy.

The upper end of multimeter measurement ranges varies considerably; measurements over perhaps 600 volts, 10 amperes, or 100 megohms may require a specialized test instrument.

Burden voltage

Any ammeter, including a multimeter in a current range, has a certain resistance. Most multimeters inherently measure voltage, and pass a current to be measured through a shunt resistance, measuring the voltage developed across it. The voltage drop is known as the burden voltage, specified in volts per ampere. The value can change depending on the range the meter selects, since different ranges usually use different shunt resistors.

The burden voltage can be significant in very low-voltage circuit areas. To check for its effect on accuracy and on external circuit operation the meter can be switched to different ranges; the current reading should be the same and circuit operation should not be affected if burden voltage is not a problem. If this voltage is significant it can be reduced (also reducing the inherent accuracy and precision of the measurement) by using a higher current range.

Alternating current sensing

Since the basic indicator system in either an analog or digital meter responds to DC only, a multimeter includes an AC to DC conversion circuit for making alternating current measurements. Basic meters utilize a rectifier circuit to measure the average or peak absolute value of the voltage, but are calibrated to show the calculated root mean square (RMS) value for a sinusoidal waveform; this will give correct readings for alternating current as used in power distribution. User guides for some such meters give correction factors for some simple non-sinusoidal waveforms, to allow the correct root mean square (RMS) equivalent value to be calculated. More expensive multimeters include an AC to DC converter that measures the true RMS value of the waveform within certain limits; the user manual for the meter may indicate the limits of the crest factor and frequency for which the meter calibration is valid. RMS sensing is necessary for measurements on non-sinusoidal periodic waveforms, such as found in audio signals and variable-frequency drives.

Digital multimeters (DMM or DVOM)
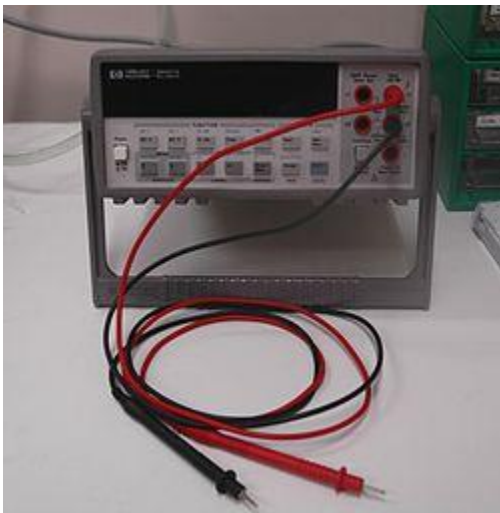
A bench-top multimeter from Hewlett-Packard.

Modern multimeters are often digital due to their accuracy, durability and extra features. In a digital multimeter the signal under test is converted to a voltage and an amplifier with electronically controlled gain preconditions the signal. A digital multimeter displays the quantity measured as a number, which eliminates parallax errors.

Modern digital multimeters may have an underline embedded computer, which provides a wealth of convenience features. Measurement enhancements available include:

- Auto-ranging, which selects the correct range for the quantity under test so that the most significant digits are shown. For example, a four-digit multimeter would automatically select an appropriate range to display 1.234 instead of 0.012, or overloading. Auto-ranging meters usually include a facility to hold the meter to a particular range, because a measurement that causes frequent range changes is distracting to the user. Other factors being equal, an auto-ranging meter will have more circuitry than an equivalent non-auto-ranging meter, and so will be more costly, but will be more convenient to use. *Auto-polarity for direct-current readings, shows if the applied voltage is positive (agrees with meter lead labels) or negative (opposite polarity to meter leads).
- Sample and hold, which will latch the most recent reading for examination after the instrument is removed from the circuit under test.
- Current-limited tests for voltage drop across semiconductor junctions. While not a replacement for a transistor tester, this facilitates testing diodes and a variety of transistor types. A graphic representation of the quantity under test, as a bar graph. This makes go/no-go testing easy, and also allows spotting of fast-moving trends.
- A low-bandwidth oscilloscope. Automotive circuit testers, including tests for automotive timing and dwell signals.
- Simple data acquisition features to record maximum and minimum readings over a given period, or to take a number of samples at fixed intervals. Integration with tweezers for surface-mount technology. A combined LCR meter for small-size SMD and through-hole components. Modern meters may be interfaced with a personal computer by IrDA links, RS-232 connections, USB, or an instrument bus such as IEEE-488. The interface allows the computer to record measurements as they are made. Some DMMs can store measurements and upload them to a computer.

Analog multimeters

Inexpensive analog multimeter with a galvanometer needle display

A multimeter may be implemented with a galvanometer meter movement, or less often with a bargraph or simulated pointer such as an LCD or vacuum fluorescent

display. Analog multimeters are common; a quality analog instrument will cost about the same as a DMM. Analog multimeters have the precision and reading accuracy limitations described above, and so are not built to provide the same accuracy as digital instruments.

Analog meters are able to display a changing reading in real time, whereas digital meters present such data in a manner that's either hard to follow or more often incomprehensible. Also an intelligible digital display can follow changes far more slowly than an analog movement, so often fails to show what's going on clearly. Some digital multimeters include a fast-responding bargraph display for this purpose, though the resolution of these is usually low.

Analog meters are also useful in situations where its necessary to pay attention to something other than the meter, and the swing of the pointer can be seen without looking at it. This can happen when accessing awkward locations, or when working on cramped live circuitry.

Analog meter movements are inherently more fragile physically and electrically than digital meters. Many analog meters have been instantly broken by connecting to the wrong point in a circuit, or while on the wrong range, or by dropping onto the floor.

The ARRL handbook also says that analog multimeters, with no electronic circuitry, are less susceptible to radio frequency interference.

The meter movement in a moving pointer analog multimeter is practically always a moving-coil galvanometer of the d'Arsonval type, using either jeweled pivots or taut bands to support the moving coil. In a basic analog multimeter the current to deflect the coil and pointer is drawn from the circuit being measured; it is usually an advantage to minimize the current drawn from the circuit. The sensitivity of an analog multimeter is given in units of ohms per volt. For example, a very low cost multimeter with a sensitivity of 1000 ohms per volt would draw 1 milliampere from a circuit at full scale deflection. More expensive, (and mechanically more delicate) multimeters typically have sensitivities of 20,000 ohms per volt and sometimes higher, with a 50,000 ohms per volt meter (drawing 20 microamperes at full scale) being about the upper limit for a portable, general purpose, non-amplified analog multimeter.

To avoid the loading of the measured circuit by the current drawn by the meter movement, some analog multimeters use an amplifier inserted between the measured circuit and the meter movement. While this increased the expense and complexity of the meter, by use of vacuum tubes or field effect transistors the input resistance can be made very high and independent of the current required to operate the meter movement coil. Such amplified multimeters are called VTVMs (vacuum tube voltmeters), TVMs (transistor volt meters), FET-VOMs, and similar names.

Probes

A multimeter can utilize a variety of test probes to connect to the circuit or device under test. Crocodile clips, retractable hook clips, and pointed probes are the three most common attachments. Tweezer probes are used for closely spaced test points, as in surface-mount devices. The connectors are attached to flexible, thickly insulated leads that are terminated with connectors appropriate for the meter. Probes are connected to portable meters typically by shrouded or recessed banana jacks, while benchtop meters may use banana jacks or BNC connectors. 2mm plugs and binding posts have also been used at times, but are less common today.

Clamp meters clamp around a conductor carrying a current to measure without the need to connect the meter in series with the circuit, or make metallic contact at all. Types to measure AC current use the transformer principle; clamp-on meters to measure small current or direct current require more complicated sensors.

Safety

All but the most inexpensive multimeters include a fuse, or two fuses, which will sometimes prevent damage to the multimeter from a current overload on the highest current range. A common error when operating a multimeter is to set the meter to measure resistance or current and then connect it directly to a low-impedance voltage source. Unfused meters are often quickly destroyed by such errors; fused meters often survive. Fuses used in meters will carry the maximum measuring current of the instrument, but are intended to clear if operator error exposes the meter to a low-impedance fault. Meters with unsafe fusing are not uncommon, this situation has led to the creation of the IEC61010 categories.

Digital meters are rated into four categories based on their intended application, as set forth by IEC 61010 -1   and echoed by country and regional standards groups such as the CEN EN61010 standard.

- Category I: used where equipment is not directly connected to the mains.
- Category II: used on single phase mains final sub-circuits.
- Category III: used on permanently installed loads such as distribution panels, motors, and 3 phase appliance outlets.
- Category IV: used on locations where fault current levels can be very high, such as supply service entrances, main panels, supply meters and primary over-voltage protection equipment.

Each category also specifies maximum transient voltages for selected measuring ranges in the meter. Category-rated meters also feature protections from over-current faults.

On meters that allow interfacing with computers, optical isolation may protect attached equipment against high voltage in the measured circuit.

DMM alternatives

A general-purpose DMM is generally considered adequate for measurements at signal levels greater than one millivolt or one milliampere, or below about 100 megohms—levels far from the theoretical limits of sensitivity. Other instruments—essentially similar, but with higher sensitivity—are used for accurate measurements of very small or very large quantities. These include nanovoltmeters, electrometers (for very low currents, and voltages with very high source resistance, such as one teraohm) and picoammeters. These measurements are limited by available technology, and ultimately by inherent thermal noise.

Power Supply

Analog meters can measure voltage and current using power from the test circuit but require internal power for resistance testing, electronic meters always require an internal power supply. Hand-held meters use batteries while bench meters usually use mains power allowing the meter to test devices not connected to a circuit. Such testing requires that the component be isolated from the circuit as otherwise other current paths will most likely distort measurements.

Meters intended for testing in hazardous locations or for use on blasting circuits may require use of a manufacturer-specified battery to maintain their safety rating.

Voltmeter

A voltmeter is an instrument used for measuring electrical potential difference between two points in an electric circuit. Analog voltmeters move a pointer across a scale in proportion to the voltage of the circuit; digital voltmeters give a numerical display of voltage by use of an analog to digital converter.

Voltmeters are made in a wide range of styles. Instruments permanently mounted in a panel are used to monitor generators or other fixed apparatus. Portable instruments, usually equipped to also measure current and resistance in the form of a multimeter, are standard test instruments used in electrical and electronics work. Any measurement that can be converted to a voltage can be displayed on a meter that is suitably calibrated; for example, pressure, temperature, flow or level in a chemical process plant.

General purpose analog voltmeters may have an accuracy of a few percent of full scale, and are used with voltages from a fraction of a volt to several thousand volts. Digital meters can be made with high accuracy, typically better than 1%.

Specially calibrated test instruments have higher accuracies, with laboratory instruments capable of measuring to accuracies of a few parts per million. Meters using amplifiers can measure tiny voltages of microvolts or less.

Part of the problem of making an accurate voltmeter is that of calibration to check its accuracy. In laboratories, the Weston Cell is used as a standard voltage for precision work. Precision voltage references are available based on electronic circuits.

Analog voltmeter

A moving coil galvanometer can be used as a voltmeter by inserting a resistor in series with the instrument. It employs a small coil of fine wire suspended in a strong magnetic field. When an electric current is applied, the galvanometer's indicator rotates and compresses a small spring. The angular rotation is proportional to the current through the coil. For use as a voltmeter, a series resistance is added so that the angular rotation becomes proportional to the applied voltage.

One of the design objectives of the instrument is to disturb the circuit as little as possible and so the instrument should draw a minimum of current to operate. This is achieved by using a sensitive ammeter or microammeter in series with a high resistance.

The sensitivity of such a meter can be expressed as "ohms per volt", the number of ohms resistance in the meter circuit divided by the full scale measured value. For example a meter with a sensitivity of 1000 ohms per volt would draw 1 milliampere at full scale voltage; if the full scale was 200 volts, the resistance at the instrument's terminals would be 200,000 ohms and at full scale the meter would draw 1 milliampere from the circuit under test. For multi-range instruments, the input resistance varies as the instrument is switched to different ranges.

Moving-coil instruments with a permanent-magnet field respond only to direct current. Measurement of AC voltage requires a rectifier in the circuit so that the coil deflects in only one direction. Moving-coil instruments are also made with the zero position in the middle of the scale instead of at one end; these are useful if the voltage reverses its polarity.

Voltmeters operating on the electrostatic principle use the mutual repulsion between two charged plates to deflect a pointer attached to a spring. Meters of this type draw negligible current but are sensitive to voltages over about 100 volts and work with either alternating or direct current.

VTVMs and FET-VMs

The sensitivity and input resistance of a voltmeter can be increased if the current required to deflect the meter pointer is supplied by an amplifier and power supply instead of by the circuit under test. The electronic amplifier between input and meter gives two benefits; a rugged moving coil instrument can be used, since its sensitivity need not be high, and the input resistance can be made high, reducing the current drawn from the circuit under test. Amplified voltmeters often have an input resistance of 1, 10, or 20 megohms which is independent of the range selected. A once-popular form of this instrument used a vacuum tube in the amplifer circuit and so was called the vacuum tube voltmeter, or VTVM. These were almost always powered by the local AC line current and so were not particularly portable. Today these circuits use a solid-state amplifier using field-effect transistors, hence FET-VM, and appear in handheld digital multimeters as well as in bench and laboratory instruments. These are now so ubiquitous that they have largely replaced non-amplified multimeters except in the least expensive price ranges.

Most VTVMs and FET-VMs handle DC voltage, AC voltage, and resistance measurements; modern FET-VMs add current measurements and often other functions as well. A specialized form of the VTVM or FET-VM is the AC voltmeter. These instruments are optimized for measuring AC voltage. They have much wider bandwidth and better sensitivity than a typical multifunction device.

Digital voltmeter

Two digital voltmeters. Note the 40 microvolt difference between the two measurements, an offset of 34 parts per million.

Digital voltmeters (DVMs) are usually designed around a special type of analog-to-digital converter called an integrating converter. Voltmeter accuracy is affected by many factors, including temperature and supply voltage variations. To ensure that a digital voltmeter's reading is within the manufacturer's specified tolerances, they should be periodically calibrated against a voltage standard such as the Weston cell.

Digital voltmeters necessarily have input amplifiers, and, like vacuum tube voltmeters, generally have a constant input resistance of 10 megohms regardless of set measurement range.

Temperature probes

A digital thermometer with a temperature probe

Voltmeters commonly allow the connection of a temperature probe, allowing them to make contact measurements of surface temperatures. The probe may be a thermistor, a thermocouple, or a temperature-dependent resistor, usually made of platinum; the probe and the instrument using it must be designed to work together.

Electric motor

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Various electric motors. A 9-volt PP3 transistor battery is in the center foreground for size comparison.

An electric motor is an electromechanical device that converts electrical energy into mechanical energy.

Most electric motors operate through the interaction of magnetic fields and current-carrying conductors to generate force. The reverse process, producing electrical energy from mechanical energy, is done by generators such as an alternator or a dynamo; some electric motors can also be used as generators, for example, a traction motor on a vehicle may perform both tasks. Electric motors and generators are commonly referred to as electric machines.

Electric motors are found in applications as diverse as industrial fans, blowers and pumps, machine tools, household appliances, power tools, and disk drives. They may be powered by direct current, e.g., a battery powered portable device or motor vehicle, or by alternating current from a central electrical distribution grid or inverter. The smallest motors may be found in electric wristwatches. Medium-size motors of highly standardized dimensions and characteristics provide convenient mechanical power for industrial uses. The very largest electric motors are used for propulsion of ships, pipeline compressors, and water pumps with ratings in the millions of watts. Electric motors may be classified by the source of electric power, by their internal construction, by their application, or by the type of motion they give.

The physical principle behind production of mechanical force by the interactions of an electric current and a magnetic field, Faraday's law of induction, was discovered by Michael Faraday in 1831. Electric motors of increasing efficiency were constructed from 1821 through the end of the 19th century, but commercial exploitation of electric motors on a large scale required efficient electrical generators and electrical distribution networks. The first commercially successful motors were made around 1873.

Some devices convert electricity into motion but do not generate usable mechanical power as a primary objective, and so are not generally referred to as electric motors. For example, magnetic solenoids and loudspeakers are usually described as actuators and transducers, respectively, instead of motors. Some electric motors are used to produce torque or force.

Terminology

In an electric motor the moving part is called the rotor and the stationary part is called the stator. Magnetic fields are produced on poles, and these can be salient poles where they are driven by windings of electrical wire. A shaded-pole motor has a winding around part of the pole that delays the phase of the magnetic field for that pole.

A commutator switches the current flow to the rotor windings depending on the rotor angle.

A DC motor is powered by direct current, although there is almost always an internal mechanism (such as a commutator) converting DC to AC for part of the motor. An AC motor is supplied with alternating current, often avoiding the need for a commutator. A synchronous motor is an AC motor that runs at a speed fixed to a fraction of the power supply frequency, and an asynchronous motor is an AC motor, usually an induction motor, whose speed slows with increasing torque to slightly less than synchronous speed. Universal motors can run on either AC or DC, though the maximum frequency of the AC supply may be limited.

Operating principle

At least 3 different operating principles are used to make electric motors: magnetism, electrostatics and piezoelectric. By far the most common is magnetic.

Magnetic

Nearly all electric motors are based around magnetism (exceptions include piezoelectric motors and ultrasonic motors). In these motors, magnetic fields are formed in both the rotor and the stator. The product between these two fields gives rise to a force, and thus a torque on the motor shaft. One, or both, of these fields must be made to change with the rotation of the motor. This is done by switching the poles on and off at the right time, or varying the strength of the pole.

Categorization

The main types are DC motors and AC motors, although the ongoing trend toward electronic control somewhat softens the distinction, as modern drivers have moved the commutator out of the motor shell for some types of DC motors.

Considering all rotating (or linear) electric motors require synchronism between a moving magnetic field and a moving current sheet for average torque production, there is a clear distinction between an asynchronous motor and synchronous types. An asynchronous motor requires slip - relative movement between the magnetic field (generated by the stator) and a winding set (the rotor) to induce current in the rotor by mutual inductance. The most ubiquitous example of asynchronous motors is the common AC induction motor which must slip to generate torque.

In the synchronous types, induction (or slip) is not a requisite for magnetic field or current production (e.g. permanent magnet motors, synchronous brush-less wound-rotor doubly fed electric machine).

Rated output power is also used to categorize motors. Those of less than 746 watts, for example, are often referred to as fractional horsepower motors (FHP) in reference to the old imperial measurement.

			Commutation		
			No commutation	Electromechanical	Electronic
			stator coils driven by line voltage	motor has a commutator to switch power to rotor coils	Switches power to stator coils, rotor position by sensing, either by discrete sensors, or feedback from coils, or open loop.
				Electro-mechanical commutator Drive	Electronic switches
			AC	DC (1)	DC
Rotor	Iron	The rotor is ferromagnetic, not	RELUCTANCE (2): • Hysteresis	Switched or variable reluctance / SRM	Switched or variable reluctance /

	permanently magnetized; it has no winding	• Synchronous reluctance		SRM • Stepper • Coilgun/mass driver
Magnet	The rotor is a permanent magnet; it has no winding	PMSM / BLAC (2) (Permanent Magnet Synchronous Motor / Brush-less Alternating Current)		BLDC (Brush-less Direct Current)
			PM (Permanent Magnet)	
Copper (usually plus magnetic core)	The rotor includes a winding	INDUCTION (3) (Squirrel cage)	WOUND STATOR: • universal(1) / series wound • shunt wound • compound wound Commutator supplies power to the coils that are best positioned to generate torque Homopolar motor (ironless rotors typical)	Frequency controlled induction motor fed from Inverter

Notes:

1. Universal motors can also work at line frequency AC (rotation is independent of the frequency of the AC voltage)
2. Rotation is synchronous with the frequency of the AC voltage
3. Rotation is always slower than synchronous.
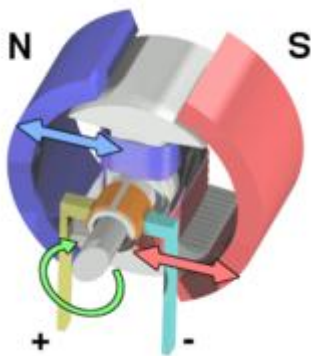
DC motors
Main article: DC motor

A DC motor is designed to run on DC electric power. Two examples of pure DC designs are Michael Faraday's homopolar motor (which is uncommon), and the ball bearing motor, which is (so far) a novelty. By far the most common DC motor types are the brushed and brushless types, which use internal and external commutation respectively to reverse the current in the windings in synchronism with rotation.

Permanent-magnet motors

A permanent-magnet motor does not have a field winding on the stator frame, instead relying on permanent magnets to provide the magnetic field against which the rotor field interacts to produce torque. Compensating windings in series with the armature may be used on large motors to improve commutation under load. Because this field is fixed, it cannot be adjusted for speed control. Permanent-magnet fields (stators) are convenient in miniature motors to eliminate the power consumption of the field winding. Most larger DC motors are of the "dynamo" type, which have stator windings. Historically, permanent magnets could not be made to retain high flux if they were disassembled; field windings were more practical to obtain the needed amount of flux. However, large permanent magnets are costly, as well as dangerous and difficult to assemble; this favors wound fields for large machines.

To minimize overall weight and size, miniature permanent-magnet motors may use high energy magnets made with neodymium or other strategic elements; most such are neodymium-iron-boron alloy. With their higher flux density, electric machines with high-energy permanent magnets are at least competitive with all optimally designed singly fed synchronous and induction electric machines. Miniature motors resemble the structure in the illustration, except that they have at least three rotor poles (to ensure starting, regardless of rotor position) and their outer housing is a steel tube that magnetically links the exteriors of the curved field magnets.

Brushed DC motors

Workings of a brushed electric motor with a two-pole rotor and permanent-magnet stator. ("N" and "S" designate polarities on the inside faces of the magnets; the outside faces have opposite polarities.)

DC motors have AC in a wound rotor also called an <u>armature</u>, with a split ring <u>commutator</u>, and either a wound or permanent magnet stator. The commutator and brushes are a long-life rotary switch. The rotor consists of one or more coils of wire wound around a laminated "soft" ferromagnetic core on a shaft; an electrical power source feeds the rotor windings through the commutator and its brushes, temporarily magnetizing the rotor core in a specific direction. The commutator switches power to the coils as the rotor turns, keeping the magnetic poles of the rotor from ever fully aligning with the magnetic poles of the stator field, so that the rotor never stops (like a compass needle does), but rather keeps rotating as long as power is applied.

Many of the limitations of the classic <u>commutator</u> DC motor are due to the need for brushes to press against the commutator. This creates <u>friction</u>. Sparks are created by the brushes making and breaking circuits through the rotor coils as the brushes cross the insulating gaps between commutator sections. Depending on the commutator design, this may include the brushes shorting together adjacent sections – and hence coil ends – momentarily while crossing the gaps. Furthermore, the <u>inductance</u> of the rotor coils causes the voltage across each to rise when its circuit is opened, increasing the sparking of the brushes. This sparking limits the maximum speed of the machine, as too-rapid sparking will overheat, erode, or even melt the commutator. The current density per unit area of the brushes, in combination with their <u>resistivity</u>, limits the output of the motor. The making and breaking of electric contact also generates <u>electrical noise</u>; sparking generates <u>RFI</u>. Brushes eventually wear out and require replacement, and the commutator itself is subject to wear and maintenance (on larger motors) or replacement (on small motors). The commutator assembly on a large motor is a costly element, requiring precision assembly of many parts. On small motors, the commutator is usually permanently integrated into the rotor, so replacing it usually requires replacing the whole rotor.

While most commutators are cylindrical, some are flat discs consisting of several segments (typically, at least three) mounted on an insulator.

Large brushes are desired for a larger brush contact area to maximize motor output, but small brushes are desired for low mass to maximize the speed at which the motor can run without the brushes excessively bouncing and sparking (comparable to the problem of "<u>valve float</u>" in internal combustion engines). (Small brushes are also desirable for lower cost.) Stiffer brush springs can also be used to make brushes of a given mass work at a higher speed, but at the cost of greater friction losses (lower efficiency) and accelerated brush and commutator wear. Therefore, DC motor brush design entails a trade-off between output power, speed, and efficiency/wear.

Notes on terminology

The first practical electric motors, used for street railways, were DC with commutators. Power was fed to the commutators (made of copper) by copper brushes, but the voltage difference between adjacent commutator bars, excellent conductivity of the copper brushes, and arcing created considerable damage after only a quite short period of operation. An electrical engineer realized that replacing the copper brushes with electrically resistive solid carbon blocks would provide much longer life. Although the term is no longer descriptive, the carbon blocks continue to be called "brushes" even to this day.

Sculptors who work with clay need support structures called armatures to keep larger works from sagging due to gravity. Magnetic laminations, in a rotor with windings, similarly support insulated-copper-wire coils. By analogy, wound rotors came to be called "armatures".[citation needed] Commutators, at least among some people who work with them daily, have become so familiar that some fail to realize that they are just a particular variety of rotary electrical switch. Considering how frequently connections make and break, they have very long lifetimes.
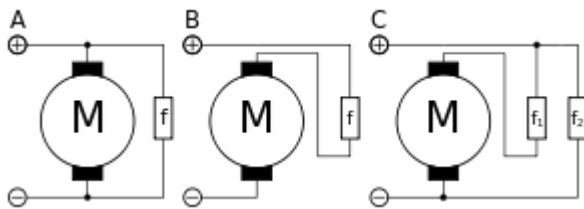
A: shunt B: series C: compound f = field coil

There are five types of brushed DC motor:

- DC shunt-wound motor
- DC series-wound motor
- DC compound motor (two configurations):
    - Cumulative compound
    - Differentially compounded
- Permanent magnet DC motor (not shown)
- Separately excited (not shown)

Brushless DC motors

Some of the problems of the brushed DC motor are eliminated in the brushless design. In this motor, the mechanical "rotating switch" or commutator/brushgear assembly is replaced by an external electronic switch synchronised to the rotor's position. Brushless motors are typically 85–90% efficient or more, efficiency for a brushless electric motor, of up to 96.5% was reported whereas DC motors with brushgear are typically 75–80% efficient.

Midway between ordinary DC motors and stepper motors lies the realm of the brushless DC motor. Built in a fashion very similar to stepper motors, these often

use a permanent magnet external rotor, three phases of driving coils, may use Hall effect sensors to sense the position of the rotor, and associated drive electronics. The coils are activated, one phase after the other, by the drive electronics as cued by the signals from either Hall effect sensors or from the back EMF (electromotive force) of the undriven coils. In effect, they act as three-phase synchronous motors containing their own variable-frequency drive electronics. A specialized class of brushless DC motor controllers utilize EMF feedback through the main phase connections instead of Hall effect sensors to determine position and velocity. These motors are used extensively in electric radio-controlled vehicles. When configured with the magnets on the outside, these are referred to by modelers as outrunner motors.

Brushless DC motors are commonly used where precise speed control is necessary, as in computer disk drives or in video cassette recorders, the spindles within CD, CD-ROM (etc.) drives, and mechanisms within office products such as fans, laser printers and photocopiers. They have several advantages over conventional motors:

- Compared to AC fans using shaded-pole motors, they are very efficient, running much cooler than the equivalent AC motors. This cool operation leads to much-improved life of the fan's bearings.
- Without a commutator to wear out, the life of a DC brushless motor can be significantly longer compared to a DC motor using brushes and a commutator. Commutation also tends to cause a great deal of electrical and RF noise; without a commutator or brushes, a brushless motor may be used in electrically sensitive devices like audio equipment or computers.
- The same Hall effect sensors that provide the commutation can also provide a convenient tachometer signal for closed-loop control (servo-controlled) applications. In fans, the tachometer signal can be used to derive a "fan OK" signal as well as provide running speed feedback.
- The motor can be easily synchronized to an internal or external clock, leading to precise speed control.
- Brushless motors have no chance of sparking, unlike brushed motors, making them better suited to environments with volatile chemicals and fuels. Also, sparking generates ozone which can accumulate in poorly ventilated buildings risking harm to occupants' health.
- Brushless motors are usually used in small equipment such as computers and are generally used in fans to get rid of unwanted heat.
- They are also acoustically very quiet motors which is an advantage if being used in equipment that is affected by vibrations.

Modern DC brushless motors range in power from a fraction of a watt to many kilowatts. Larger brushless motors up to about 100 kW rating are used in electric vehicles. They also find significant use in high-performance electric model aircraft.

Switched reluctance motors
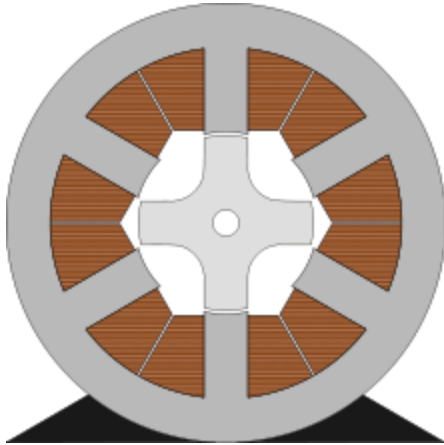
6/4 Pole Switched reluctance motor
Main article: Switched reluctance motor

The switched reluctance motor (SRM) has no brushes or permanent magnets, and the rotor has no electric currents. Instead, torque comes from a slight mis-alignment of poles on the rotor with poles on the stator. The rotor aligns itself with the magnetic field of the stator, while the stator field stator windings are sequentially energized to rotate the stator field.

The magnetic flux created by the field windings follows the path of least magnetic reluctance, meaning the flux will flow through poles of the rotor that are closest to the energized poles of the stator, thereby magnitizing those poles of the rotor and creating torque. As the rotor turns, different windings will be energized, keeping the rotor turning.

Switched reluctance motors are now being used in some appliances.

Coreless or ironless DC motors

Nothing in the principle of any of the motors described above requires that the iron (steel) portions of the rotor actually rotate. If the soft magnetic material of the rotor is made in the form of a cylinder, then (except for the effect of hysteresis) torque is exerted only on the windings of the electromagnets. Taking advantage of this fact is the coreless or ironless DC motor, a specialized form of a brush or brushless DC motor. Optimized for rapid acceleration, these motors have a rotor that is constructed without any iron core. The rotor can take the form of a winding-filled cylinder, or a self-supporting structure comprising only the magnet wire and the bonding material. The rotor can fit inside the stator magnets; a magnetically soft stationary cylinder inside the rotor provides a return path for the stator magnetic flux. A second arrangement has the rotor winding basket surrounding the stator magnets. In that design, the rotor fits inside a magnetically

soft cylinder that can serve as the housing for the motor, and likewise provides a return path for the flux.

Because the rotor is much lighter in weight (mass) than a conventional rotor formed from copper windings on steel laminations, the rotor can accelerate much more rapidly, often achieving a mechanical time constant under 1 ms. This is especially true if the windings use aluminum rather than the heavier copper. But because there is no metal mass in the rotor to act as a heat sink, even small coreless motors must often be cooled by forced air. Overheating might be an issue for coreless DC motor designs.

Among these types are the disc-rotor types, described in more detail in the next section.

Vibrator motors for cellular phones are sometimes tiny cylindrical permanent-magnet field types, but there are also disc-shaped types which have a thin multipolar disc field magnet, and an intentionally unbalanced molded-plastic rotor structure with two bonded coreless coils. Metal brushes and a flat commutator switch power to the rotor coils.

Related limited-travel actuators have no core and a bonded coil placed between the poles of high-flux thin permanent magnets. These are the fast head positioners for rigid-disk ("hard disk") drives. Although the contemporary design differs considerably from that of loudspeakers, it is still loosely (and incorrectly) referred to as a "voice coil" structure, because some earlier rigid-disk-drive heads moved in straight lines, and had a drive structure much like that of a loudspeaker.

Printed armature or pancake DC motors

A rather unusual motor design, the printed armature or pancake motor has the windings shaped as a disc running between arrays of high-flux magnets. The magnets are arranged in a circle facing the rotor with space in between to form an axial air gap. This design is commonly known as the pancake motor because of its extremely flat profile, although the technology has had many brand names since its inception, such as ServoDisc.

The printed armature (originally formed on a printed circuit board) in a printed armature motor is made from punched copper sheets that are laminated together using advanced composites to form a thin rigid disc. The printed armature has a unique construction in the brushed motor world in that it does not have a separate ring commutator. The brushes run directly on the armature surface making the whole design very compact.

An alternative manufacturing method is to use wound copper wire laid flat with a central conventional commutator, in a flower and petal shape. The windings are typically stabilized by being impregnated with electrical epoxy potting systems.

These are filled epoxies that have moderate mixed viscosity and a long gel time. They are highlighted by low shrinkage and low exotherm, and are typically UL 1446 recognized as a potting compound for use up to 180°C (Class H) (UL File No. E 210549).

The unique advantage of ironless DC motors is that there is no cogging (torque variations caused by changing attraction between the iron and the magnets). Parasitic eddy currents cannot form in the rotor as it is totally ironless, although iron rotors are laminated. This can greatly improve efficiency, but variable-speed controllers must use a higher switching rate (>40 kHz) or direct current because of the decreased electromagnetic induction.

These motors were originally invented to drive the capstan(s) of magnetic tape drives in the burgeoning computer industry, where minimal time to reach operating speed and minimal stopping distance were critical. Pancake motors are still widely used in high-performance servo-controlled systems, humanoid robotic systems, industrial automation and medical devices. Due to the variety of constructions now available, the technology is used in applications from high temperature military to low cost pump and basic servos.

Universal motors
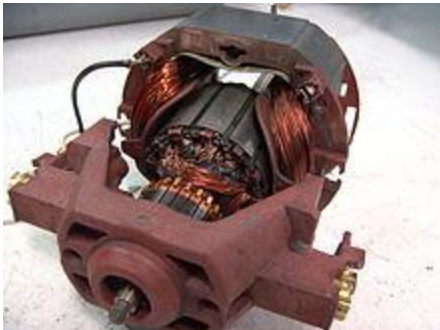
Modern low-cost universal motor, from a vacuum cleaner. Field windings are dark copper colored, toward the back, on both sides. The rotor's laminated core is gray metallic, with dark slots for winding the coils. The commutator (partly hidden) has become dark from use; it's toward the front. The large brown molded-plastic piece in the foreground supports the brush guides and brushes (both sides), as well as the front motor bearing.

A series-wound motor is referred to as a universal motor when it has been designed to operate on either AC or DC power. It can operate well on AC because the current in both the field and the armature (and hence the resultant magnetic fields) will alternate (reverse polarity) in synchronism, and hence the resulting mechanical force will occur in a constant direction of rotation.

Operating at normal power line frequencies, universal motors are often found in a range rarely larger than 1000 watt. Universal motors also form the basis of the traditional railway traction motor in electric railways. In this application, the use of

AC to power a motor originally designed to run on DC would lead to efficiency losses due to eddy current heating of their magnetic components, particularly the motor field pole-pieces that, for DC, would have used solid (un-laminated) iron. Although the heating effects are reduced by using laminated pole-pieces, as used for the cores of transformers and by the use of laminations of high permeability electrical steel, one solution available at start of the 20th century was for the motors to be operated from very low frequency AC supplies, with 25 and 16.7 Hz operation being common. Because they used universal motors, locomotives using this design were also commonly capable of operating from a third rail or overhead wire powered by DC. As well, considering that steam engines directly powered many alternators, their relatively low speeds favored low frequencies because comparatively few stator poles were needed.

An advantage of the universal motor is that AC supplies may be used on motors which have some characteristics more common in DC motors, specifically high starting torque and very compact design if high running speeds are used. The negative aspect is the maintenance and short life problems caused by the commutator. Such motors are used in devices such as food mixers and power tools which are used only intermittently, and often have high starting-torque demands. Continuous speed control of a universal motor running on AC is easily obtained by use of a thyristor circuit, while multiple taps on the field coil provide (imprecise) stepped speed control. Household blenders that advertise many speeds frequently combine a field coil with several taps and a diode that can be inserted in series with the motor (causing the motor to run on half-wave rectified AC).

In the past, repulsion-start wound-rotor motors provided high starting torque, but with added complexity. Their rotors were similar to those of universal motors, but their brushes were connected only to each other. Transformer action induced current into the rotor. Brush position relative to field poles meant that starting torque was developed by rotor repulsion from the field poles. A centrifugal mechanism, when close to running speed, connected all commutator bars together to create the equivalent of a squirrel-cage rotor. As well, when close to operating speed, better motors lifted the brushes out of contact.

Induction motors cannot turn a shaft faster than allowed by the power line frequency. By contrast, universal motors generally run at high speeds, making them useful for appliances such as blenders, vacuum cleaners, and hair dryers where high speed and light weight is desirable. They are also commonly used in portable power tools, such as drills, sanders, circular and jig saws, where the motor's characteristics work well. Many vacuum cleaner and weed trimmer motors exceed 10,000 RPM, while many Dremel and similar miniature grinders exceed 30,000 RPM.

Universal motors also lend themselves to electronic speed control and, as such, are an ideal choice for domestic washing machines. The motor can be used to

agitate the drum (both forwards and in reverse) by switching the field winding with respect to the armature. The motor can also be run up to the high speeds required for the spin cycle.

Motor damage may occur from overspeeding (running at a rotational speed in excess of design limits) if the unit is operated with no significant load. On larger motors, sudden loss of load is to be avoided, and the possibility of such an occurrence is incorporated into the motor's protection and control schemes. In some smaller applications, a <u>fan blade</u> attached to the shaft often acts as an artificial load to limit the motor speed to a safe level, as well as a means to circulate cooling airflow over the armature and field windings.

AC motors

An AC motor has two parts: a stationary stator having coils supplied with alternating current to produce a rotating magnetic field, and a rotor attached to the output shaft that is given a torque by the rotating field.

AC motor with sliding rotor

A conical-rotor brake motor incorporates the brake as an integral part of the conical sliding rotor. When the motor is at rest, a spring acts on the sliding rotor and forces the brake ring against the brake cap in the motor, holding the rotor stationary. When the motor is energized, its magnetic field generates both an axial and a radial component. The axial component overcomes the spring force, releasing the brake; while the radial component causes the rotor to turn. There is no additional brake control required.

Synchronous electric motor

A synchronous electric motor is an AC motor distinguished by a rotor spinning with coils passing magnets at the same rate as the alternating current and resulting magnetic field which drives it. Another way of saying this is that it has zero slip under usual operating conditions. Contrast this with an induction motor, which must slip to produce torque. One type of synchronous motor is like an induction motor except the rotor is excited by a DC field. Slip rings and brushes are used to conduct current to the rotor. The rotor poles connect to each other and move at the same speed hence the name synchronous motor. Another type, for low load torque, has flats ground onto a conventional squirrel-cage rotor to create discrete poles. Yet another, such as made by Hammond for its pre-World War II clocks, and in the older Hammond organs, has no rotor windings and discrete poles. It is not self-starting. The clock requires manual starting by a small knob on the back, while the older Hammond organs had an auxiliary starting motor connected by a spring-loaded manually operated switch.

Finally, hysteresis synchronous motors typically are (essentially) two-phase motors with a phase-shifting capacitor for one phase. They start like induction motors, but when slip rate decreases sufficiently, the rotor (a smooth cylinder) becomes temporarily magnetized. Its distributed poles make it act like a permanent-magnet-rotor synchronous motor. The rotor material, like that of a common nail, will stay magnetized, but can also be demagnetized with little difficulty. Once running, the rotor poles stay in place; they do not drift.

Low-power synchronous timing motors (such as those for traditional electric clocks) may have multi-pole permanent-magnet external cup rotors, and use shading coils to provide starting torque. Telechron clock motors have shaded poles for starting torque, and a two-spoke ring rotor that performs like a discrete two-pole rotor.

Induction motor

An induction motor is an asynchronous AC motor where power is transferred to the rotor by electromagnetic induction, much like transformer action. An induction motor resembles a rotating transformer, because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side. Polyphase induction motors are widely used in industry.

Induction motors may be further divided into squirrel-cage motors and wound-rotor motors. Squirrel-cage motors have a heavy winding made up of solid bars, usually aluminum or copper, joined by rings at the ends of the rotor. When one considers only the bars and rings as a whole, they are much like an animal's rotating exercise cage, hence the name.

Currents induced into this winding provide the rotor magnetic field. The shape of the rotor bars determines the speed-torque characteristics. At low speeds, the current induced in the squirrel cage is nearly at line frequency and tends to be in the outer parts of the rotor cage. As the motor accelerates, the slip frequency becomes lower, and more current is in the interior of the winding. By shaping the bars to change the resistance of the winding portions in the interior and outer parts of the cage, effectively a variable resistance is inserted in the rotor circuit. However, the majority of such motors have uniform bars.

In a wound-rotor motor, the rotor winding is made of many turns of insulated wire and is connected to slip rings on the motor shaft. An external resistor or other control devices can be connected in the rotor circuit. Resistors allow control of the motor speed, although significant power is dissipated in the external resistance. A converter can be fed from the rotor circuit and return the slip-frequency power that would otherwise be wasted back into the power system through an inverter or separate motor-generator.

The wound-rotor induction motor is used primarily to start a high inertia load or a load that requires a very high starting torque across the full speed range. By correctly selecting the resistors used in the secondary resistance or slip ring starter, the motor is able to produce maximum torque at a relatively low supply current from zero speed to full speed. This type of motor also offers controllable speed.

Motor speed can be changed because the torque curve of the motor is effectively modified by the amount of resistance connected to the rotor circuit. Increasing the value of resistance will move the speed of maximum torque down. If the resistance connected to the rotor is increased beyond the point where the maximum torque occurs at zero speed, the torque will be further reduced.

When used with a load that has a torque curve that increases with speed, the motor will operate at the speed where the torque developed by the motor is equal to the load torque. Reducing the load will cause the motor to speed up, and increasing the load will cause the motor to slow down until the load and motor torque are equal. Operated in this manner, the slip losses are dissipated in the secondary resistors and can be very significant. The speed regulation and net efficiency is also very poor.

Various regulatory authorities in many countries have introduced and implemented legislation to encourage the manufacture and use of higher efficiency electric motors. There is existing and forthcoming legislation regarding the future mandatory use of premium-efficiency induction-type motors in defined equipment. For more information, see: Premium efficiency and Copper in energy efficient motors.

Doubly fed electric motor

Main article: Doubly fed electric machine

Doubly fed electric motors have two independent multiphase winding sets, which contribute active (i.e., working) power to the energy conversion process, with at least one of the winding sets electronically controlled for variable speed operation. Two independent multiphase winding sets (i.e., dual armature) are the maximum provided in a single package without topology duplication. Doubly fed electric motors are machines with an effective constant torque speed range that is twice synchronous speed for a given frequency of excitation. This is twice the constant torque speed range as singly fed electric machines, which have only one active winding set.

A doubly fed motor allows for a smaller electronic converter but the cost of the rotor winding and slip rings may offset the saving in the power electronics components. Difficulties with controlling speed near synchronous speed limit applications.

Singly fed electric motor

Main article: Singly fed electric machine

Most AC motors are singly fed. Singly fed electric motors have a single multiphase winding set that is connected to a power supply. Singly fed electric machines may be either induction or synchronous. The active winding set can be electronically controlled. Singly fed electric machines have an effective constant torque speed range up to synchronous speed for a given excitation frequency.

Torque motors

A torque motor (also known as a limited torque motor) is a specialized form of induction motor which is capable of operating indefinitely while stalled, that is, with the rotor blocked from turning, without incurring damage. In this mode of operation, the motor will apply a steady torque to the load (hence the name).

A common application of a torque motor would be the supply- and take-up reel motors in a tape drive. In this application, driven from a low voltage, the characteristics of these motors allow a relatively constant light tension to be applied to the tape whether or not the capstan is feeding tape past the tape heads. Driven from a higher voltage, (and so delivering a higher torque), the torque motors can also achieve fast-forward and rewind operation without requiring any additional mechanics such as gears or clutches. In the computer gaming world, torque motors are used in force feedback steering wheels.

Another common application is the control of the throttle of an internal combustion engine in conjunction with an electronic governor. In this usage, the motor works against a return spring to move the throttle in accordance with the output of the governor. The latter monitors engine speed by counting electrical pulses from the ignition system or from a magnetic pickup and, depending on the speed, makes small adjustments to the amount of current applied to the motor. If the engine starts to slow down relative to the desired speed, the current will be increased, the motor will develop more torque, pulling against the return spring and opening the throttle. Should the engine run too fast, the governor will reduce the current being applied to the motor, causing the return spring to pull back and close the throttle.

Stepper motors
Main article: Stepper motor

Closely related in design to three-phase AC synchronous motors are stepper motors, where an internal rotor containing permanent magnets or a magnetically soft rotor with salient poles is controlled by a set of external magnets that are switched electronically. A stepper motor may also be thought of as a cross between a DC electric motor and a rotary solenoid. As each coil is energized in

turn, the rotor aligns itself with the magnetic field produced by the energized field winding. Unlike a synchronous motor, in its application, the stepper motor may not rotate continuously; instead, it "steps"—starts and then quickly stops again—from one position to the next as field windings are energized and de-energized in sequence. Depending on the sequence, the rotor may turn forwards or backwards, and it may change direction, stop, speed up or slow down arbitrarily at any time.

Simple stepper motor drivers entirely energize or entirely de-energize the field windings, leading the rotor to "cog" to a limited number of positions; more sophisticated drivers can proportionally control the power to the field windings, allowing the rotors to position between the cog points and thereby rotate extremely smoothly. This mode of operation is often called microstepping. Computer controlled stepper motors are one of the most versatile forms of positioning systems, particularly when part of a digital servo-controlled system.

Stepper motors can be rotated to a specific angle in discrete steps with ease, and hence stepper motors are used for read/write head positioning in computer floppy diskette drives. They were used for the same purpose in pre-gigabyte era computer disk drives, where the precision and speed they offered was adequate for the correct positioning of the read/write head of a hard disk drive. As drive density increased, the precision and speed limitations of stepper motors made them obsolete for hard drives—the precision limitation made them unusable, and the speed limitation made them uncompetitive—thus newer hard disk drives use voice coil-based head actuator systems. (The term "voice coil" in this connection is historic; it refers to the structure in a typical (cone type) loudspeaker. This structure was used for a while to position the heads. Modern drives have a pivoted coil mount; the coil swings back and forth, something like a blade of a rotating fan. Nevertheless, like a voice coil, modern actuator coil conductors (the magnet wire) move perpendicular to the magnetic lines of force.)

Stepper motors were and still are often used in computer printers, optical scanners, and digital photocopiers to move the optical scanning element, the print head carriage (of dot matrix and inkjet printers), and the platen or feed rollers. Likewise, many computer plotters (which since the early 1990s have been replaced with large-format inkjet and laser printers) used rotary stepper motors for pen and platen movement; the typical alternatives here were either linear stepper motors or servomotors with closed-loop analog control systems.

So-called quartz analog wristwatches contain the smallest commonplace stepping motors; they have one coil, draw very little power, and have a permanent-magnet rotor. The same kind of motor drives battery-powered quartz clocks. Some of these watches, such as chronographs, contain more than one stepping motor.

Stepper motors were upscaled to be used in electric vehicles under the term SRM (<u>Switched Reluctance Motor</u>).

Comparison

Comparison of motor types

Type	Advantages	Disadvantages	Typical Application	Typical Drive
AC polyphase induction squirrel-cage	Low cost, long life, high efficiency, large ratings available (to 1 MW or more), large number of standardized types	Starting inrush current can be high, speed control requires variable frequency source	Pumps, fans, blowers, conveyors, compressors	Poly-phase AC, variable frequency AC
<u>Shaded-pole motor</u>	Low cost Long life	Speed slightly below synchronous Low starting torque Small ratings low efficiency	Fans, appliances, record players	Single phase AC
AC induction – Squirrel cage, split-phase capacitor-start	High power high starting torque	Speed slightly below synchronous Starting switch or relay required	Appliances Stationary Power Tools	Single phase AC
AC induction – Squirrel cage, split-phase capacitor-run	Moderate power High starting torque No starting switch Comparatively long life	Speed slightly below synchronous Slightly more costly	Industrial blowers Industrial machinery	Single phase AC
AC induction – Squirrel cage motor, split-phase, auxiliary start winding	Moderate power Low starting torque	Speed slightly below synchronous Starting switch or relay required	Appliances Stationary Power Tools	Single phase AC
<u>Universal motor</u>	High starting torque, compact, high	Maintenance (brushes) Shorter lifespan	Handheld power tools, blenders,	Single phase AC or DC

	speed.	Usually acoustically noisy Only small ratings are economic	vacuum cleaners, insulation blowers	
AC Synchronous	Synchronous speed	More costly	Industrial motors Clocks Audio turntables Tape drives	Single or Polyphase AC (Capacitor-run for single-phase)
Stepper DC	Precision positioning High holding torque	Some can be costly Require a controller	Positioning in printers and floppy disc drives; industrial machine tools	DC
Brushless DC	Long lifespan Low maintenance High efficiency	Higher initial cost Requires a controller	Rigid ("hard") disk drives CD/DVD players Electric vehicles RC Vehicles UAVs	DC or PWM
Switched reluctance motor	Long lifespan Low maintenance High efficiency No permanent magnets Low cost Simple construction	Requires a controller	Appliances Electric Vehicles Textile mills Aircraft applications	DC or PWM
Brushed DC	Simple speed control	Maintenance (brushes) Medium lifespan Costly commutator and brushes	Steel mills Paper making machines Treadmill exercisers Automotive accessories	Direct DC or PWM
Pancake DC	Compact design Simple speed control	Medium cost Medium lifespan	Office Equip Fans/Pumps, fast industrial and military servos	Direct DC or PWM

Back EMF

During operation the conductors that make up the coils of a motor will see external varying magnetic fields, either due to their own motion, or the movement or varying of other magnets, and these generate electrical potentials across the coils called 'back EMF' that are in the opposite direction to the power supply, and are proportional to the running speed of the motor.

Since the difference in voltage of the power supply and the back EMF determine the current in the coils, this also determines the torque generated by the motor at any instant in time as well as the heat generated in the resistance of the windings.

Thus motor running speeds can often be reasonably well controlled in many motors by simply applying a fixed voltage- the speed will tend to increase until the back-EMF cancels out most of the applied voltage.

Electrostatic

Full size

An electrostatic motor is based on the attraction and repulsion of electric charge. Usually, electrostatic motors are the dual of conventional coil-based motors. They typically require a high voltage power supply, although very small motors employ lower voltages. Conventional electric motors instead employ magnetic attraction and repulsion, and require high current at low voltages. In the 1750s, the first electrostatic motors were developed by Benjamin Franklin and Andrew Gordon. Today the electrostatic motor finds frequent use in micro-mechanical (MEMS) systems where their drive voltages are below 100 volts, and where moving, charged plates are far easier to fabricate than coils and iron cores. Also, the molecular machinery which runs living cells is often based on linear and rotary electrostatic motors.

Piezoelectric

Main article: Piezoelectric motor

A piezoelectric motor or piezo motor is a type of electric motor based upon the change in shape of a piezoelectric material when an electric field is applied. Piezoelectric motors make use of the converse piezoelectric effect whereby the material produces acoustic or ultrasonic vibrations in order to produce a linear or rotary motion. In one mechanism, the elongation in a single plane is used to

make a series stretches and position holds, similar to the way a <u>caterpillar</u> moves.

Use and styles

Standardized electric motors are often used in many modern machines but specific types of electric motors are designed for particular applications.

Rotary

Uses include rotating machines such as fans, turbines, drills, the wheels on electric cars, locomotives and conveyor belts. Also, in many vibrating or oscillating machines, an electric motor spins an unbalanced mass, causing the motor (and its mounting structure) to vibrate. A familiar application is cell phone vibrating alerts used when the acoustic "ringer" is disabled by the user.

Electric motors are also popular in robotics. They turn the wheels of vehicular robots, and servo motors operate arms in industrial robots; they also move arms and legs in humanoid robots. In flying robots, along with helicopters, a motor rotates a propeller, or aerodynamic rotor blades to create controllable amounts of lift.

Electric motors are replacing <u>hydraulic cylinders</u> in airplanes and military equipment.

In industrial and manufacturing businesses, electric motors rotate saws and blades in cutting and slicing processes; they rotate parts being turned in lathes and other machine tools, and spin grinding wheels. Fast, precise servo motors position tools and work in modern CNC machine tools. Motor-driven mixers are very common in food manufacturing. Linear motors are often used to push products into containers horizontally.

Many kitchen appliances also use electric motors. Food processors and grinders spin blades to chop and break up foods. Blenders use electric motors to mix liquids, and microwave ovens use motors to turn the tray that food sits on. Toaster ovens also use electric motors to turn a conveyor to move food over heating elements.

Servo motor

A servomotor is a motor, very often sold as a complete module, which is used within a position-control or speed-control feedback control system. Servomotors are used in applications such as machine tools, pen plotters, and other control systems. Motors intended for use in a servomechanism must have well-documented characteristics for speed, torque, and power. The speed vs. torque curve is quite important. Dynamic response characteristics such as winding

inductance and rotor inertia are also important; these factors limit the overall performance of the servomechanism loop. Large, powerful, but slow-responding servo loops may use conventional AC or DC motors and drive systems with position or speed feedback on the motor. As dynamic response requirements increase, more specialized motor designs such as coreless motors are used.

A servo system differs from some stepper motor applications in that the position feedback is continuous while the motor is running; a stepper system relies on the motor not to "miss steps" for short term accuracy, although a stepper system may include a "home" switch or other element to provide long-term stability of control. For instance, when an ink-jet computer printer starts up, its controller makes the print head stepper motor drive to its left-hand limit, where a position sensor defines home position and stops stepping. As long as power is on, a bidirectional counter in the printer's microprocessor keeps track of print-head position.

Linear motor

A linear motor is essentially any electric motor that has been "unrolled" so that, instead of producing a torque (rotation), it produces a straight-line force along its length.

Linear motors are most commonly induction motors or stepper motors. Linear motors are commonly found in many roller-coasters where the rapid motion of the motorless railcar is controlled by the rail. They are also used in maglev trains, where the train "flies" over the ground. On a smaller scale, the HP 7225A pen plotter, released in 1978, used two linear stepper motors to move the pen along the X and Y axes.

Generator

Many electric motors are used as generators, either part (such as regenerative braking) or all of their operational life. When mechanically driven magnetic electric motors produce power due to their back EMF.

Performance

Specifying an electric motor

When specifying what type of electric motor is needed, the mechanical power available at the shaft is used. This means that users can predict the torque and speed of the motor without having to know the mechanical losses associated with the motor. Example: 10 kW induction motor.

Power

The power output of a rotary electric motor is:

$$P = \frac{rpm \times T}{5252}$$

Where P is in horsepower, rpm is the shaft speed in revolutions per minute and T is the torque in foot pounds.

And for a linear motor:

$$P = F \times v$$

Where P is the power in watts, and F is in Newtons and v is the speed in metres per second.

Efficiency

To calculate a motor's efficiency, the mechanical output power is divided by the electrical input power: $\eta = \frac{P_m}{P_e}$, where η is energy conversion efficiency, P_e is electrical input power, and P_m is mechanical output power.

In simplest case $P_e = VI$, and $P_m = T\omega$, where V is input voltage, I is input current, T is output torque, and ω is output angular velocity. It is possible to derive analytically the point of maximum efficiency. It is typically at less than 1/2 the stall torque.

Torque capability of motor types

When optimally designed within a given core saturation constraint and for a given active current (i.e., torque current), voltage, pole-pair number, excitation frequency (i.e., synchronous speed), and air-gap flux density, all categories of electric motors or generators will exhibit virtually the same maximum continuous shaft torque (i.e., operating torque) within a given air-gap area with winding slots and back-iron depth, which determines the physical size of electromagnetic core. Some applications require bursts of torque beyond the maximum operating torque, such as short bursts of torque to accelerate an electric vehicle from standstill. Always limited by magnetic core saturation or safe operating temperature rise and voltage, the capacity for torque bursts beyond the maximum operating torque differs significantly between categories of electric motors or generators.

Capacity for bursts of torque should not be confused with field weakening capability inherent in fully electromagnetic electric machines (Permanent Magnet (PM) electric machine are excluded). Field weakening, which is not available with

PM electric machines, allows an electric machine to operate beyond the designed frequency of excitation.

Electric machines without a transformer circuit topology, such as Field-Wound (i.e., electromagnet) or Permanent Magnet (PM) Synchronous electric machines cannot realize bursts of torque higher than the maximum designed torque without saturating the magnetic core and rendering any increase in current as useless. Furthermore, the permanent magnet assembly of PM synchronous electric machines can be irreparably damaged, if bursts of torque exceeding the maximum operating torque rating are attempted.

Electric machines with a transformer circuit topology, such as Induction (i.e., asynchronous) electric machines, Induction Doubly Fed electric machines, and Induction or Synchronous Wound-Rotor Doubly Fed (WRDF) electric machines, exhibit very high bursts of torque because the active current (i.e., Magneto-Motive-Force or the product of current and winding-turns) induced on either side of the transformer oppose each other and as a result, the active current contributes nothing to the transformer coupled magnetic core flux density, which would otherwise lead to core saturation.

Electric machines that rely on Induction or Asynchronous principles short-circuit one port of the transformer circuit and as a result, the reactive impedance of the transformer circuit becomes dominant as slip increases, which limits the magnitude of active (i.e., real) current. Still, bursts of torque that are two to three times higher than the maximum design torque are realizable.

The Synchronous WRDF electric machine is the only electric machine with a truly dual ported transformer circuit topology (i.e., both ports independently excited with no short-circuited port). The dual ported transformer circuit topology is known to be unstable and requires a multiphase slip-ring-brush assembly to propagate limited power to the rotor winding set. If a precision means were available to instantaneously control torque angle and slip for synchronous operation during motoring or generating while simultaneously providing brushless power to the rotor winding set (see Brushless wound-rotor doubly fed electric machine), the active current of the Synchronous WRDF electric machine would be independent of the reactive impedance of the transformer circuit and bursts of torque significantly higher than the maximum operating torque and far beyond the practical capability of any other type of electric machine would be realizable. Torque bursts greater than eight times operating torque have been calculated.

Continuous torque density

The continuous torque density of conventional electric machines is determined by the size of the air-gap area and the back-iron depth, which are determined by the power rating of the armature winding set, the speed of the machine, and the achievable air-gap flux density before core saturation. Despite the high coercivity

of neodymium or samarium-cobalt permanent magnets, continuous torque density is virtually the same amongst electric machines with optimally designed armature winding sets. Continuous torque density should never be confused with peak torque density, which comes with the manufacturer's chosen method of cooling, which is available to all, or period of operation before destruction by overheating of windings or even permanent magnet damage.

Switch

In electronics, a switch is an electrical component that can break an electrical circuit, interrupting the current or diverting it from one conductor to another.

The most familiar form of switch is a manually operated electromechanical device with one or more sets of electrical contacts, which are connected to external circuits. Each set of contacts can be in one of two states: either "closed" meaning the contacts are touching and electricity can flow between them, or "open", meaning the contacts are separated and the switch is non-conducting. The mechanism actuating the transition between these two states (open or closed) can be either a "toggle" (flip switch for continuous "on" or "off") or "momentary" (push-for "on" or push-for "off") type.

A switch may be directly manipulated by a human as a control signal to a system, such as a computer keyboard button, or to control power flow in a circuit, such as a light switch. Automatically operated switches can be used to control the motions of machines, for example, to indicate that a garage door has reached its full open position or that a machine tool is in a position to accept another work piece. Switches may be operated by process variables such as pressure, temperature, flow, current, voltage, and force, acting as sensors in a process and used to automatically control a system. For example, a thermostat is a temperature-operated switch used to control a heating process. A switch that is operated by another electrical circuit is called a relay. Large switches may be remotely operated by a motor drive mechanism. Some switches are used to isolate electric power from a system, providing a visible point of isolation that can be pad-locked if necessary to prevent accidental operation of a machine during maintenance, or to prevent electric shock.

In circuit theory

In electronics engineering, an ideal switch describes a switch that:

- has no current limit during its ON state
- has infinite resistance during its OFF state
- has no voltage drop across the switch during its ON state
- has no voltage limit during its OFF state
- has zero rise time and fall time during state changes
- switches without "bouncing" between on and off positions

Practical switches fall short of this ideal, and have resistance, limits on the current and voltage they can handle, finite switching time, etc. The ideal switch is often used in circuit analysis as it greatly simplifies the system of equations to be solved, however this can lead to a less accurate solution.

Contacts

In the simplest case, a switch has two conductive pieces, often metal, called contacts, connected to an external circuit, that touch to complete (make) the circuit, and separate to open (break) the circuit. The contact material is chosen for its resistance to corrosion, because most metals form insulating oxides that would prevent the switch from working. Contact materials are also chosen on the basis of electrical conductivity, hardness (resistance to abrasive wear), mechanical strength, low cost and low toxicity.

Sometimes the contacts are plated with noble metals. They may be designed to wipe against each other to clean off any contamination. Nonmetallic conductors, such as conductive plastic, are sometimes used. To prevent the formation of insulating oxides, a minimum wetting current may be specified for a given switch design.
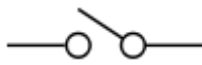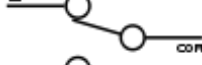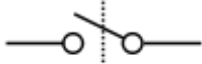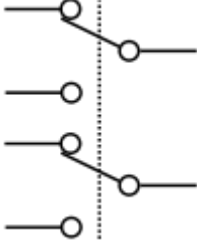
Contact terminology
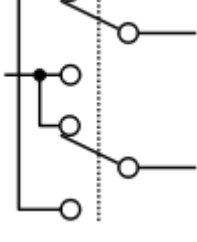
Switches are classified according to the arrangement of their contacts in electronics. A pair of contacts is said to be "closed" when current can flow from one to the other. When the contacts are separated by an insulating air gap, they are said to be "open", and no current can flow between them at normal voltages. The terms "make" for closure of contacts and "break" for opening of contacts are also widely used.

In a push-button type switch, in which the contacts remain in one state unless actuated, the contacts can either be normally open (abbreviated "n.o." or "no") until closed by operation of the switch, or normally closed ("n.c. or "nc") and opened by the switch action. A switch with both types of contact is called a changeover switch. These may be "make-before-break" which momentarily connect both circuits, or may be "break-before-make" which interrupts one circuit before closing the other.

The terms pole and throw are also used to describe switch contact variations. The number of "poles" is the number of separate circuits which are controlled by a switch. For example, a "2-pole" switch has two separate identical sets of contacts controlled by the same knob. The number of "throws" is the number of separate positions that the switch can adopt. A single-throw switch has one pair of contacts that can either be closed or open. A double-throw switch has a contact that can be connected to either of two other contacts, a triple-throw has a contact which can be connected to one of three other contacts, etc.

These terms give rise to abbreviations for the types of switch which are used in the electronics industry such as "single-pole, single-throw" (SPST) (the simplest type, "on or off") or "single-pole, double-throw" (SPDT), connecting either of two terminals to the common terminal. In electrical power wiring (i.e. house and building wiring by electricians) names generally involving the suffixed word "-way" are used; however, these terms differ between British and American English and the terms two way and three way are used in both with different meanings.

Electronics specification and abbreviation	Expansion of abbreviation	British mains wiring name	American electrical wiring name	Description	Symbol
SPST	Single pole, single throw	One-way	Two-way	A simple on-off switch: The two terminals are either connected together or disconnected from each other. An example is a light switch.	
SPDT	Single pole, double throw	Two-way	Three-way	A simple changeover switch: C (COM, Common) is connected to L1 or to L2.	
SPCO SPTT, c.o.	Single pole changeover or Single pole, centre off or Single Pole, Triple Throw			Similar to SPDT. Some suppliers use SPCO/SPTT for switches with a stable off position in the centre and SPDT for those without.[citation needed]	
DPST	Double pole, single throw	Double pole	Double pole	Equivalent to two SPST switches controlled by a single mechanism	

DPDT	Double pole, double throw	Equivalent to two SPDT switches controlled by a single mechanism.	
DPCO	Double pole changeover or Double pole, centre off	Equivalent to DPDT. Some suppliers use DPCO for switches with a stable off position in the centre and DPDT for those without.	
Intermediate switch	Four-way switch	DPDT switch internally wired for polarity-reversal applications: only four rather than six wires are brought outside the switch housing.	

Switches with larger numbers of poles or throws can be described by replacing the "S" or "D" with a number (e.g. 3PST, 4PST, etc.) or in some cases the letter "T" (for "triple"). In the rest of this article the terms SPST, SPDT and intermediate will be used to avoid the ambiguity.

Contact bounce

Contact bounce (also called chatter) is a common problem with mechanical switches and relays. Switch and relay contacts are usually made of springy metals that are forced into contact by an actuator. When the contacts strike together, their momentum and elasticity act together to cause bounce. The result is a rapidly pulsed electric current instead of a clean transition from zero to full current. The effect is usually unimportant in power circuits, but causes problems in some analogue and logic circuits that respond fast enough to misinterpret the on-off pulses as a data stream. The effects of contact bounce can be eliminated by use of mercury-wetted contacts, but these are now infrequently used because of the hazard of mercury release.

Contact circuits can be filtered to reduce or eliminate multiple pulses. In digital systems, multiple samples of the contact state can be taken or a time delay can be implemented so that the contact bounce has settled before the contact input is used to control anything. One way to implement this with an SPDT Switch is by using an SR Latch.

Arcs and quenching

When the power being switched is sufficiently large, the electron flow across opening switch contacts is sufficient to ionize the air molecules across the tiny gap between the contacts as the switch is opened, forming a gas plasma, also known as an electric arc. The plasma is of low resistance and is able to sustain power flow, even with the separation distance between the switch contacts steadily increasing. The plasma is also very hot and is capable of eroding the metal surfaces of the switch contacts. Electric current arcing causes significant degradation of the contacts and also significant electromagnetic interference (EMI), requiring the use of arc suppression methods.

Where the voltage is sufficiently high, an arc can also form as the switch is closed and the contacts approach. If the voltage potential is sufficient to exceed the breakdown voltage of the air separating the contacts, an arc forms which is sustained until the switch closes completely and the switch surfaces make contact.

In either case, the standard method for minimizing arc formation and preventing contact damage is to use a fast-moving switch mechanism, typically using a spring-operated tipping-point mechanism to assure quick motion of switch contacts, regardless of the speed at which the switch control is operated by the user. Movement of the switch control lever applies tension to a spring until a tipping point is reached, and the contacts suddenly snap open or closed as the spring tension is released.

As the power being switched increases, other methods are used to minimize or prevent arc formation. A plasma is hot and will rise due to convection air currents. The arc can be quenched with a series of nonconductive blades spanning the distance between switch contacts, and as the arc rises its length increases as it forms ridges rising into the spaces between the blades, until the arc is too long to stay sustained and is extinguished. A puffer may be used to blow a sudden high velocity burst of gas across the switch contacts, which rapidly extends the length of the arc to extinguish it quickly.

Extremely large switches in excess of 100,000 watts capacity often have switch contacts surrounded by something other than air to more rapidly extinguish the arc. For example, the switch contacts may operate in a vacuum, immersed in mineral oil, or in sulfur hexafluoride.

In AC power service, the current periodically passes through zero; this effect makes it harder to sustain an arc on opening. As a consequence, safety certification agencies commonly issue two maximum voltage ratings for switches and fuses, one for AC service and one for DC service.

Power switching

When a switch is designed to switch significant power, the transitional state of the switch as well as the ability to stand continuous operating currents must be considered. When a switch is in the on state its resistance is near zero and very little power is dropped in the contacts; when a switch is in the off state its resistance is extremely high and even less power is dropped in the contacts. However when the switch is flicked the resistance must pass through a state where briefly a quarter (or worse if the load is not purely resistive) of the load's rated power is dropped in the switch.

For this reason, power switches intended to interrupt a load current have spring mechanisms to make sure the transition between on and off is as short as possible regardless of the speed at which the user moves the rocker.

Power switches usually come in two types. A momentary on-off switch (such as on a laser pointer) usually takes the form of a button and only closes the circuit when the button is depressed. A regular on-off switch (such as on a flashlight) has a constant on-off feature. Dual-action switches incorporate both of these features.

Inductive loads

When a strongly inductive load such as an electric motor is switched off, the current cannot drop instantaneously to zero; a spark will jump across the opening contacts. Switches for inductive loads must be rated to handle these cases. The spark will cause electromagnetic interference if not suppressed; a snubber network of a resistor and capacitor in series will quell the spark.

Incandescent loads

Incandescent lamps present a large load when turned on. The cold resistance of the lamp filament briefly allows an inrush current of about ten times the steady-state current to flow through the switch contacts. As the filament heats up, its resistance rises and the current decreases to a steady-state value. Switch and relay contacts formulated for incandescent lamp service carry separate incandescent load ratings that may differ from their inductive and resistive load ratings.

Wetting current

Wetting current is the minimum current needing to flow through a mechanical switch while it is operated to break through any film of oxidation that may have been deposited on the switch contacts. [8]The film of oxidation occurs often in areas with high humidity. Providing a sufficient amount of wetting current is a crucial step in designing systems that use delicate switches with small contact pressure as sensor inputs. Failing to do this might result in switches remaining electrically 'open' due to contact oxidation.

Actuator

The moving part that applies the operating force to the contacts is called the actuator, and may be a toggle or dolly, a rocker, a push-button or any type of mechanical linkage (see photo).

Biased switches

The momentary push-button switch is a type of biased switch. The most common type is a "push-to-make" (or normally-open or NO) switch, which makes contact when the button is pressed and breaks when the button is released. Each key of a computer keyboard, for example, is a normally-open "push-to-make" switch. A "push-to-break" (or normally-closed or NC) switch, on the other hand, breaks contact when the button is pressed and makes contact when it is released. An example of a push-to-break switch is a button used to release a door held open by an electromagnet. The interior lamp of a household refrigerator is controlled by a switch that is held open when the door is closed.

Commercially available switches are available which can be wired to operate either normally-open or normally-closed, having two sets of contacts. Depending on the application the installer or electrician may choose whichever mode is appropriate.

Multi-throw switches are also found with a bias position. The last throw of a rotary switch may be biased to return to the penultimate position once the operator releases their hold of it.

Toggle switch

A toggle switch is a class of electrical switches that are manually actuated by a mechanical lever, handle, or rocking mechanism.

Toggle switches are available in many different styles and sizes, and are used in countless applications. Many are designed to provide the simultaneous actuation of multiple sets of electrical contacts, or the control of large amounts of electric current or mains voltages.

The word "toggle" is a reference to a kind of mechanism or joint consisting of two arms, which are almost in line with each other, connected with an elbow-like pivot. However, the phrase "toggle switch" is applied to a switch with a short handle and a positive snap-action, whether it actually contains a toggle mechanism or not. Similarly, a switch where a definitive click is heard, is called a "positive on-off switch".

Special types

Switches can be designed to respond to any type of mechanical stimulus: for example, vibration (the trembler switch), tilt, air pressure, fluid level (a float switch), the turning of a key (key switch), linear or rotary movement (a limit switch or microswitch), or presence of a magnetic field (the reed switch). Many switches are operated automatically by changes in some environmental condition or by motion of machinery. A limit switch is used, for example, in machine tools to interlock operation with the proper position of tools. In heating or cooling systems a sail switch ensures that air flow is adequate in a duct. Pressure switches respond to fluid pressure.

Mercury tilt switch

The mercury switch consists of a drop of mercury inside a glass bulb with 2 or more contacts. The two contacts pass through the glass, and are connected by the mercury when the bulb is tilted to make the mercury roll on to them.

This type of switch performs much better than the ball tilt switch, as the liquid metal connection is unaffected by dirt, debris and oxidation, it wets the contacts ensuring a very low resistance bounce-free connection, and movement and vibration do not produce a poor contact. These types can be used for precision works.

It can also be used where arcing is dangerous (such as in the presence of explosive vapour) as the entire unit is sealed.

Knife switch

Knife switches consist of a flat metal blade, hinged at one end, with an insulating handle for operation, and a fixed contact. When the switch is closed, current flows through the hinged pivot and blade and through the fixed contact. Such switches are usually not enclosed. The knife and contacts are typically formed of copper, steel, or brass, depending on the application. Fixed contacts may be backed up with a spring. Several parallel blades can be operated at the same time by one handle. The parts may be mounted on an insulating base with terminals for wiring, or may be directly bolted to an insulated switch board in a large assembly. Since the electrical contacts are exposed, the switch is used

only where people cannot accidentally come in contact with the switch or where the voltage is so low as to not present a hazard.

Knife switches are made in many sizes from miniature switches to large devices used to carry thousands of amperes. In electrical transmission and distribution, gang-operated switches are used in circuits up to the highest voltages.

The disadvantages of the knife switch are the slow opening speed and the proximity of the operator to exposed live parts. Metal-enclosed safety disconnect switches are used for isolation of circuits in industrial power distribution. Sometimes spring-loaded auxiliary blades are fitted which momentarily carry the full current during opening, then quickly part to rapidly extinguish the arc.

Footswitch

A footswitch is a rugged switch which is operated by foot pressure. An example of use is for the control of an electric sewing machine. The foot control of an electric guitar is also a switch.

Reversing switch

A DPDT switch has six connections, but since polarity reversal is a very common usage of DPDT switches, some variations of the DPDT switch are internally wired specifically for polarity reversal. These crossover switches only have four terminals rather than six. Two of the terminals are inputs and two are outputs. When connected to a battery or other DC source, the 4-way switch selects from either normal or reversed polarity. Such switches can also be used as intermediate switches in a multiway switching system for control of lamps by more than two switches.

Light switches

In building wiring, light switches are installed at convenient locations to control lighting and occasionally other circuits. By use of multiple-pole switches, multiway switching control of a lamp can be obtained from two or more places, such as the ends of a corridor or stairwell. A wireless light switch allows remote control of lamps for convenience; some lamps include a touch switch which electronically controls the lamp if touched anywhere. In public buildings several types of vandal resistant switch are used to prevent unauthorized use.

Electronic switches

A relay is an electrically operated switch. Many relays use an electromagnet to operate a switching mechanism mechanically, but other operating principles are also used. Solid-state relays control power circuits with no moving parts, instead

using a semiconductor device to perform switching—often a <u>silicon-controlled rectifier</u> or <u>triac</u>.

The <u>analogue switch</u> uses two MOSFET transistors in a <u>transmission gate</u> arrangement as a switch that works much like a relay, with some advantages and several limitations compared to an electromechanical relay.

The power transistor(s) in a <u>switching voltage regulator</u>, such as a <u>power supply unit</u>, are used like a switch to alternately let power flow and block power from flowing.

Sensor

A sensor (also called detector) is a <u>converter</u> that measures a <u>physical quantity</u> and converts it into a signal which can be read by an observer or by an (today mostly <u>electronic</u>) instrument. For example, a <u>mercury-in-glass thermometer</u> converts the measured temperature into expansion and contraction of a liquid which can be read on a calibrated glass tube. A <u>thermocouple</u> converts temperature to an output voltage which can be read by a <u>voltmeter</u>. For accuracy, most sensors are <u>calibrated</u> against known <u>standards</u>.

Sensors are used in everyday objects such as touch-sensitive elevator buttons (<u>tactile sensor</u>) and lamps which dim or brighten by touching the base. There are also innumerable applications for sensors of which most people are never aware. Applications include cars, machines, aerospace, medicine, manufacturing and robotics.

A sensor is a device which receives and responds to a signal. A sensor's sensitivity indicates how much the sensor's output changes when the measured quantity changes. For instance, if the mercury in a thermometer moves 1 cm when the temperature changes by 1 °C, the sensitivity is 1 cm/°C (it is basically the slope Dy/Dx assuming a linear characteristic). Sensors that measure very small changes must have very high sensitivities. Sensors also have an impact on what they measure; for instance, a room temperature thermometer inserted into a hot cup of liquid cools the liquid while the liquid heats the thermometer. Sensors need to be designed to have a small effect on what is measured; making the sensor smaller often improves this and may introduce other advantages.

Classification of measurement errors

A good sensor obeys the following rules:

- Is sensitive to the measured property only
- Is insensitive to any other property likely to be encountered in its application

- Does not influence the measured property

Ideal sensors are designed to be <u>linear</u> or linear to some simple mathematical function of the measurement, typically <u>logarithmic</u>. The output signal of such a sensor is <u>linearly proportional</u> to the value or simple function of the measured property. The <u>sensitivity</u> is then defined as the ratio between output signal and measured property. For example, if a sensor measures temperature and has a voltage output, the sensitivity is a constant with the unit [V/K]; this sensor is linear because the ratio is constant at all points of measurement.

Sensor deviations

If the sensor is not ideal, several types of deviations can be observed:

- The <u>sensitivity</u> may in practice differ from the value specified. This is called a sensitivity error, but the sensor is still linear.
- Since the range of the output signal is always limited, the output signal will eventually reach a minimum or maximum when the measured property exceeds the limits. The full scale range defines the maximum and minimum values of the measured property.
- If the output signal is not zero when the measured property is zero, the sensor has an <u>offset</u> or <u>bias</u>. This is defined as the output of the sensor at zero input.
- If the sensitivity is not constant over the range of the sensor, this is called <u>non linearity</u>. Usually this is defined by the amount the output differs from ideal behavior over the full range of the sensor, often noted as a percentage of the full range.
- If the deviation is caused by a rapid change of the measured property over time, there is a <u>dynamic</u> error. Often, this behavior is described with a <u>bode plot</u> showing sensitivity error and phase shift as function of the frequency of a periodic input signal.
- If the output signal slowly changes independent of the measured property, this is defined as <u>drift (telecommunication)</u>.
- <u>Long term drift</u> usually indicates a slow degradation of sensor properties over a long period of time.
- <u>Noise</u> is a random deviation of the signal that varies in time.
- <u>Hysteresis</u> is an error caused by when the measured property reverses direction, but there is some finite lag in time for the sensor to respond, creating a different offset error in one direction than in the other.
- If the sensor has a digital output, the output is essentially an approximation of the measured property. The approximation error is also called <u>digitization</u> error.
- If the signal is monitored digitally, limitation of the <u>sampling frequency</u> also can cause a dynamic error, or if the variable or added noise noise changes periodically at a frequency near a multiple of the sampling rate may induce <u>aliasing</u> errors.

- The sensor may to some extent be sensitive to properties other than the property being measured. For example, most sensors are influenced by the temperature of their environment.

All these deviations can be classified as systematic errors or random errors. Systematic errors can sometimes be compensated for by means of some kind of calibration strategy. Noise is a random error that can be reduced by signal processing, such as filtering, usually at the expense of the dynamic behavior of the sensor.

Resolution

The resolution of a sensor is the smallest change it can detect in the quantity that it is measuring. Often in a digital display, the least significant digit will fluctuate, indicating that changes of that magnitude are only just resolved. The resolution is related to the precision with which the measurement is made. For example, a scanning tunneling probe (a fine tip near a surface collects an electron tunnelling current) can resolve atoms and molecules.

Types
Main article: List of sensors

Sensors in nature

All living organisms contain biological sensors with functions similar to those of the mechanical devices described. Most of these are specialized cells that are sensitive to:

- Light, motion, temperature, magnetic fields, gravity, humidity, moisture, vibration, pressure, electrical fields, sound, and other physical aspects of the external environment
- Physical aspects of the internal environment, such as stretch, motion of the organism, and position of appendages (proprioception)
- Environmental molecules, including toxins, nutrients, and pheromones
- Estimation of biomolecules interaction and some kinetics parameters
- Internal metabolic milieu, such as glucose level, oxygen level, or osmolality
- Internal signal molecules, such as hormones, neurotransmitters, and cytokines
- Differences between proteins of the organism itself and of the environment or alien creatures.

Relay

A relay is an electrically operated switch. Many relays use an electromagnet to operate a switching mechanism mechanically, but other operating principles are

also used. Relays are used where it is necessary to control a circuit by a low-power signal (with complete electrical isolation between control and controlled circuits), or where several circuits must be controlled by one signal. The first relays were used in long distance telegraph circuits, repeating the signal coming in from one circuit and re-transmitting it to another. Relays were used extensively in telephone exchanges and early computers to perform logical operations.

A type of relay that can handle the high power required to directly control an electric motor or other loads is called a contactor. Solid-state relays control power circuits with no moving parts, instead using a semiconductor device to perform switching. Relays with calibrated operating characteristics and sometimes multiple operating coils are used to protect electrical circuits from overload or faults; in modern electric power systems these functions are performed by digital instruments still called "protective relays".

Basic design and operation

A simple electromagnetic relay consists of a coil of wire wrapped around a soft iron core, an iron yoke which provides a low reluctance path for magnetic flux, a movable iron armature, and one or more sets of contacts (there are two in the relay pictured). The armature is hinged to the yoke and mechanically linked to one or more sets of moving contacts. It is held in place by a spring so that when the relay is de-energized there is an air gap in the magnetic circuit. In this condition, one of the two sets of contacts in the relay pictured is closed, and the other set is open. Other relays may have more or fewer sets of contacts depending on their function. The relay in the picture also has a wire connecting the armature to the yoke. This ensures continuity of the circuit between the moving contacts on the armature, and the circuit track on the printed circuit board (PCB) via the yoke, which is soldered to the PCB.

When an electric current is passed through the coil it generates a magnetic field that activates the armature, and the consequent movement of the movable contact(s) either makes or breaks (depending upon construction) a connection with a fixed contact. If the set of contacts was closed when the relay was de-energized, then the movement opens the contacts and breaks the connection, and vice versa if the contacts were open. When the current to the coil is switched off, the armature is returned by a force, approximately half as strong as the magnetic force, to its relaxed position. Usually this force is provided by a spring, but gravity is also used commonly in industrial motor starters. Most relays are manufactured to operate quickly. In a low-voltage application this reduces noise; in a high voltage or current application it reduces arcing.

When the coil is energized with direct current, a diode is often placed across the coil to dissipate the energy from the collapsing magnetic field at deactivation, which would otherwise generate a voltage spike dangerous to semiconductor circuit components. Some automotive relays include a diode inside the relay

case. Alternatively, a contact protection network consisting of a capacitor and resistor in series (snubber circuit) may absorb the surge. If the coil is designed to be energized with alternating current (AC), a small copper "shading ring" can be crimped to the end of the solenoid, creating a small out-of-phase current which increases the minimum pull on the armature during the AC cycle.

A solid-state relay uses a thyristor or other solid-state switching device, activated by the control signal, to switch the controlled load, instead of a solenoid. An optocoupler (a light-emitting diode (LED) coupled with a photo transistor) can be used to isolate control and controlled circuits.

Types

Latching relay

A latching relay has two relaxed states (bistable). These are also called "impulse", "keep", or "stay" relays. When the current is switched off, the relay remains in its last state. This is achieved with a solenoid operating a ratchet and cam mechanism, or by having two opposing coils with an over-center spring or permanent magnet to hold the armature and contacts in position while the coil is relaxed, or with a remanent core. In the ratchet and cam example, the first pulse to the coil turns the relay on and the second pulse turns it off. In the two coil example, a pulse to one coil turns the relay on and a pulse to the opposite coil turns the relay off. This type of relay has the advantage that one coil consumes power only for an instant, while it is being switched, and the relay contacts retain this setting across a power outage. A remanent core latching relay requires a current pulse of opposite polarity to make it change state.

Reed relay

A reed relay is a reed switch enclosed in a solenoid. The switch has a set of contacts inside an evacuated or inert gas-filled glass tube which protects the contacts against atmospheric corrosion; the contacts are made of magnetic material that makes them move under the influence of the field of the enclosing solenoid. Reed relays can switch faster than larger relays, require only little power from the control circuit, but have low switching current and voltage ratings. In addition, the reeds can become magnetized over time, which makes them stick 'on' even when no current is present; changing the orientation of the reeds with respect to the solenoid's magnetic field will fix the problem.

Mercury-wetted relay

A mercury-wetted reed relay is a form of reed relay in which the contacts are wetted with mercury. Such relays are used to switch low-voltage signals (one volt or less) where the mercury reduces the contact resistance and associated voltage drop, for low-current signals where surface contamination may make for

a poor contact, or for high-speed applications where the mercury eliminates contact bounce. Mercury wetted relays are position-sensitive and must be mounted vertically to work properly. Because of the toxicity and expense of liquid mercury, these relays are now rarely used. See also mercury switch.

Polarized relay

A polarized relay placed the armature between the poles of a permanent magnet to increase sensitivity. Polarized relays were used in middle 20th Century telephone exchanges to detect faint pulses and correct telegraphic distortion. The poles were on screws, so a technician could first adjust them for maximum sensitivity and then apply a bias spring to set the critical current that would operate the relay.

- External links
  - Schematic diagram of a polarized relay used in a teletype machine.

Machine tool relay

A machine tool relay is a type standardized for industrial control of machine tools, transfer machines, and other sequential control. They are characterized by a large number of contacts (sometimes extendable in the field) which are easily converted from normally-open to normally-closed status, easily replaceable coils, and a form factor that allows compactly installing many relays in a control panel. Although such relays once were the backbone of automation in such industries as automobile assembly, the programmable logic controller (PLC) mostly displaced the machine tool relay from sequential control applications.

A relay allows circuits to be switched by electrical equipment: for example, a timer circuit with a relay could switch power at a preset time. For many years relays were the standard method of controlling industrial electronic systems. A number of relays could be used together to carry out complex functions (relay logic). The principle of relay logic is based on relays which energize and de-energize associated contacts. Relay logic is the predecessor of ladder logic, which is commonly used in Programmable logic controllers.

Ratchet relay

This is again a clapper type relay which does not need continuous current through its coil to retain its operation.
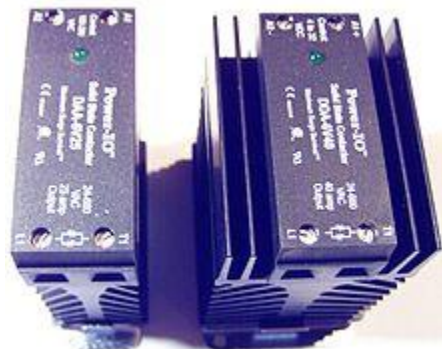
Contactor relay

A contactor is a very heavy-duty relay used for switching electric motors and lighting loads, although contactors are not generally called relays. Continuous current ratings for common contactors range from 10 amps to several hundred

amps. High-current contacts are made with alloys containing silver. The unavoidable arcing causes the contacts to oxidize; however, silver oxide is still a good conductor. Such devices are often used for motor starters. A motor starter is a contactor with overload protection devices attached. The overload sensing devices are a form of heat operated relay where a coil heats a bi-metal strip, or where a solder pot melts, releasing a spring to operate auxiliary contacts. These auxiliary contacts are in series with the coil. If the overload senses excess current in the load, the coil is de-energized. Contactor relays can be extremely loud to operate, making them unfit for use where noise is a chief concern.

Solid-state relay
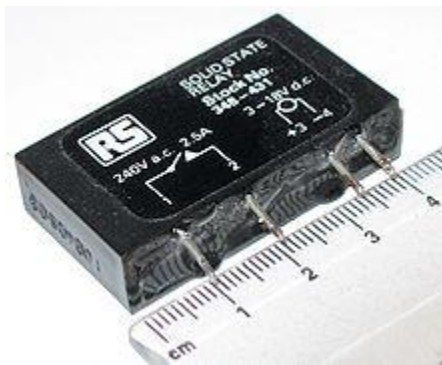
Solid state relay with no moving parts

25 A or 40 A solid state contactors

A solid state relay (SSR) is a solid state electronic component that provides a similar function to an electromechanical relay but does not have any moving components, increasing long-term reliability. Every solid-state device has a small voltage drop across it. This voltage drop limited the amount of current a given SSR could handle. The minimum voltage drop for such a relay is a function of the material used to make the device. Solid-state relays rated to handle as much as 1,200 Amperes, have become commercially available. Compared to electromagnetic relays, they may be falsely triggered by transients.

Solid state contactor relay

A solid state contactor is a heavy-duty solid state relay, including the necessary heat sink, used for switching electric heaters, small electric motors and lighting loads; where frequent on/off cycles are required. There are no moving parts to wear out and there is no contact bounce due to vibration. They are activated by AC control signals or DC control signals from Programmable logic controller (PLCs), PCs, Transistor-transistor logic (TTL) sources, or other microprocessor and microcontroller controls.

Buchholz relay

A Buchholz relay is a safety device sensing the accumulation of gas in large oil-filled transformers, which will alarm on slow accumulation of gas or shut down the transformer if gas is produced rapidly in the transformer oil.

Forced-guided contacts relay

A forced-guided contacts relay has relay contacts that are mechanically linked together, so that when the relay coil is energized or de-energized, all of the linked contacts move together. If one set of contacts in the relay becomes immobilized, no other contact of the same relay will be able to move. The function of forced-guided contacts is to enable the safety circuit to check the status of the relay. Forced-guided contacts are also known as "positive-guided contacts", "captive contacts", "locked contacts", or "safety relays".

Overload protection relay

Electric motors need overcurrent protection to prevent damage from over-loading the motor, or to protect against short circuits in connecting cables or internal faults in the motor windings. One type of electric motor overload protection relay is operated by a heating element in series with the electric motor. The heat generated by the motor current heats a bimetallic strip or melts solder, releasing a spring to operate contacts. Where the overload relay is exposed to the same environment as the motor, a useful though crude compensation for motor ambient temperature is provided.

Pole and throw
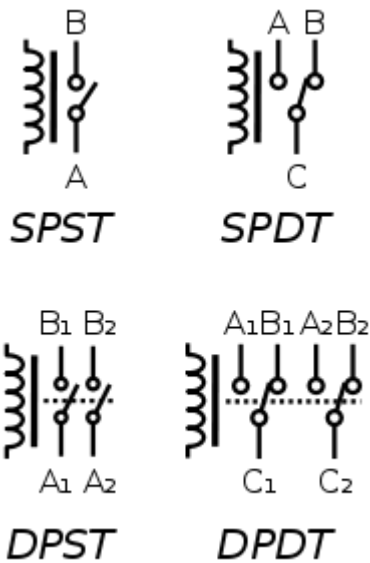
Circuit symbols of relays. (C denotes the common terminal in SPDT and DPDT types.)

Since relays are <u>switches</u>, the terminology applied to switches is also applied to relays. A relay will switch one or more poles, each of whose contacts can be thrown by energizing the coil in one of three ways:

- Normally-open (NO) contacts connect the circuit when the relay is activated; the circuit is disconnected when the relay is inactive. It is also called a Form A contact or "make" contact. NO contacts can also be distinguished as "early-make" or NOEM, which means that the contacts will close before the button or switch is fully engaged.
- Normally-closed (NC) contacts disconnect the circuit when the relay is activated; the circuit is connected when the relay is inactive. It is also called a Form B contact or "break" contact. NC contacts can also be distinguished as "late-break" or NCLB, which means that the contacts will stay closed until the button or switch is fully disengaged.
- Change-over (CO), or double-throw (DT), contacts control two circuits: one normally-open contact and one normally-closed contact with a common terminal. It is also called a Form C contact or "transfer" contact ("break before make"). If this type of contact utilizes a "make before break" functionality, then it is called a Form D contact.

The following designations are commonly encountered:

- SPST – Single Pole Single Throw. These have two terminals which can be connected or disconnected. Including two for the coil, such a relay has four terminals in total. It is ambiguous whether the pole is normally open or

normally closed. The terminology "SPNO" and "SPNC" is sometimes used to resolve the ambiguity.

- SPDT – Single Pole Double Throw. A common terminal connects to either of two others. Including two for the coil, such a relay has five terminals in total.
- DPST – Double Pole Single Throw. These have two pairs of terminals. Equivalent to two SPST switches or relays actuated by a single coil. Including two for the coil, such a relay has six terminals in total. The poles may be Form A or Form B (or one of each).
- DPDT – Double Pole Double Throw. These have two rows of change-over terminals. Equivalent to two SPDT switches or relays actuated by a single coil. Such a relay has eight terminals, including the coil.

The "S" or "D" may be replaced with a number, indicating multiple switches connected to a single actuator. For example 4PDT indicates a four pole double throw relay (with 14 terminals).

EN 50005 are among applicable standards for relay terminal numbering; a typical EN 50005-compliant SPDT relay's terminals would be numbered 11, 12, 14, A1 and A2 for the C, NC, NO, and coil connections, respectively.

Applications

Relays are used to and for:

- Amplify a digital signal, switching a large amount of power with a small operating power. Some special cases are:
  - A telegraph relay, repeating a weak signal received at the end of a long wire
  - Controlling a high-voltage circuit with a low-voltage signal, as in some types of modems or audio amplifiers,
  - Controlling a high-current circuit with a low-current signal, as in the starter solenoid of an automobile,
- Detect and isolate faults on transmission and distribution lines by opening and closing circuit breakers (protection relays),

A DPDT AC coil relay with "ice cube" packaging

- Isolate the controlling circuit from the controlled circuit when the two are at different potentials, for example when controlling a mains-powered device from a low-voltage switch. The latter is often applied to control office lighting as the low voltage wires are easily installed in partitions, which may be often moved as needs change. They may also be controlled by room occupancy detectors to conserve energy,
- Logic functions. For example, the boolean AND function is realised by connecting normally open relay contacts in series, the OR function by connecting normally open contacts in parallel. The change-over or Form C contacts perform the XOR (exclusive or) function. Similar functions for NAND and NOR are accomplished using normally closed contacts. The Ladder programming language is often used for designing relay logic networks.
    - The application of Boolean Algebra to relay circuit design was formalized by Claude Shannon in A Symbolic Analysis of Relay and Switching Circuits
    - Early computing. Before vacuum tubes and transistors, relays were used as logical elements in digital computers. See electro-mechanical computers such as ARRA (computer), Harvard Mark II, Zuse Z2, and Zuse Z3.
    - Safety-critical logic. Because relays are much more resistant than semiconductors to nuclear radiation, they are widely used in safety-critical logic, such as the control panels of radioactive waste-handling machinery.
- Time delay functions. Relays can be modified to delay opening or delay closing a set of contacts. A very short (a fraction of a second) delay would use a copper disk between the armature and moving blade assembly. Current flowing in the disk maintains magnetic field for a short time, lengthening release time. For a slightly longer (up to a minute) delay, a dashpot is used. A dashpot is a piston filled with fluid that is allowed to escape slowly. The time period can be varied by increasing or decreasing the flow rate. For longer time periods, a mechanical clockwork timer is installed.
- Vehicle battery isolation. A 12v relay is often used to isolate any second battery in cars, 4WDs, RVs and boats.
- Switching to a standby power supply.

Relay application considerations

Selection of an appropriate relay for a particular application requires evaluation of many different factors:

- Number and type of contacts – normally open, normally closed, (double-throw)

- Contact sequence – "Make before Break" or "Break before Make". For example, the old style telephone exchanges required Make-before-break so that the connection didn't get dropped while dialing the number.
- Rating of contacts – small relays switch a few amperes, large contactors are rated for up to 3000 amperes, alternating or direct current
- Voltage rating of contacts – typical control relays rated 300 VAC or 600 VAC, automotive types to 50 VDC, special high-voltage relays to about 15 000 V
- Operating lifetime, useful life - the number of times the relay can be expected to operate reliably. There is both a mechanical life and a contact life; the contact life is naturally affected by the kind of load being switched.
- Coil voltage – machine-tool relays usually 24 VDC, 120 or 250 VAC, relays for switchgear may have 125 V or 250 VDC coils, "sensitive" relays operate on a few milliamperes
- Coil current - including minimum current required to operate reliably and minimum current to hold. Also effects of power dissipation on coil temperature at various duty cycles.
- Package/enclosure – open, touch-safe, double-voltage for isolation between circuits, explosion proof, outdoor, oil and splash resistant, washable for printed circuit board assembly
- Operating environment - minimum and maximum operating temperatures and other environmental considerations such as effects of humidity and salt
- Assembly – Some relays feature a sticker that keeps the enclosure sealed to allow PCB post soldering cleaning, which is removed once assembly is complete.
- Mounting – sockets, plug board, rail mount, panel mount, through-panel mount, enclosure for mounting on walls or equipment
- Switching time – where high speed is required
- "Dry" contacts – when switching very low level signals, special contact materials may be needed such as gold-plated contacts
- Contact protection – suppress arcing in very inductive circuits
- Coil protection – suppress the surge voltage produced when switching the coil current
- Isolation between coil contacts
- Aerospace or radiation-resistant testing, special quality assurance
- Expected mechanical loads due to acceleration – some relays used in aerospace applications are designed to function in shock loads of 50 g or more
- Accessories such as timers, auxiliary contacts, pilot lamps, test buttons
- Regulatory approvals
- Stray magnetic linkage between coils of adjacent relays on a printed circuit board.

There are many considerations involved in the correct selection of a control relay for a particular application. These considerations include factors such as speed

of operation, sensitivity, and <u>hysteresis</u>. Although typical control relays operate in the 5 ms to 20 ms range, relays with switching speeds as fast as 100 us are available. <u>Reed relays</u> which are actuated by low currents and switch fast are suitable for controlling small currents.

As for any switch, the current through the relay contacts (unrelated to the current through the coil) must not exceed a certain value to avoid damage. In the particular case of high-<u>inductance</u> circuits such as <u>motors</u> other issues must be addressed. When a power source is connected to an inductance, an <u>input surge current</u> which may be several times larger than the steady current exists. When the circuit is broken, the current cannot change instantaneously, which creates a potentially damaging spark across the separating contacts.

Consequently for relays which may be used to control inductive loads we must specify the maximum current that may flow through the relay contacts when it actuates, the make rating; the continuous rating; and the break rating. The make rating may be several times larger than the continuous rating, which is itself larger than the break rating.

Derating factors

Control relays should not be operated above rated temperature because of resulting increased degradation and fatigue. Common practice is to derate 20 degrees Celsius from the maximum rated temperature limit. Relays operating at rated load are also affected by their environment. Oil vapors may greatly decrease the contact tip life, and dust or dirt may cause the tips to burn before

Type of load	% of rated value
Resistive	75
Inductive	35
Motor	20
Filament	10
Capacitive	75

their normal life expectancy. Control relay life cycle varies from 50,000 to over one million cycles depending on the electrical loads of the contacts, <u>duty cycle</u>, application, and the extent to which the relay is derated. When a control relay is operating at its derated value, it is controlling a lower value of current than its maximum make and break ratings. This is often done to extend the operating life of the control relay. The table lists the relay derating factors for typical industrial control applications.

Undesired arcing

<u>Arc suppression</u>

Without adequate <u>contact protection</u>, the occurrence of <u>electric current arcing</u> causes significant degradation of the contacts in relays, which suffer significant and visible damage. Every time a relay transitions either from a closed to an open state (break arc) or from an open to a closed state (make arc & bounce arc), under load, an electrical arc can occur between the two contact points

(electrodes) of the relay. The break arc is typically more energetic and thus more destructive.

The heat energy contained in the resulting electrical arc is very high (tens of thousands of degrees Fahrenheit), causing the metal on the contact surfaces to melt, pool and migrate with the current. The extremely high temperature of the arc cracks the surrounding gas molecules creating ozone, carbon monoxide, and other compounds. The arc energy slowly destroys the contact metal, causing some material to escape into the air as fine particulate matter. This very activity causes the material in the contacts to degrade quickly, resulting in device failure. This contact degradation drastically limits the overall life of a relay to a range of about 10,000 to 100,000 operations, a level far below the mechanical life of the same device, which can be in excess of 20 million operations.

Protective relays
Main article: protective relay

For protection of electrical apparatus and transmission lines, electromechanical relays with accurate operating characteristics were used to detect overload, short-circuits, and other faults. While many such relays remain in use, digital devices now provide equivalent protective functions.

a protective relay is an electromechanical apparatus, often with more than one coil, designed to calculate operating conditions on an electrical circuit and trip circuit breakers when a fault is detected. Unlike switching type relays with fixed and usually ill-defined operating voltage thresholds and operating times, protective relays have well-established, selectable, time/current (or other operating parameter) operating characteristics. Protection relays may use arrays of induction disks, shaded-pole magnets, operating and restraint coils, solenoid-type operators, telephone-relay contacts, and phase-shifting networks. Protection relays respond to such conditions as over-current, over-voltage, reverse power flow, over- and under- frequency. Distance relays trip for faults up to a certain distance away from a substation but not beyond that point. An important transmission line or generator unit will have cubicles dedicated to protection, with many individual electromechanical devices. The various protective functions available on a given relay are denoted by standard ANSI Device Numbers. For example, a relay including function 51 would be a timed overcurrent protective relay.

Electromechanical protective relays at a hydroelectric generating plant

Design and theory of these protective devices is an important part of the education of an electrical engineer who specializes in power systems. Today these devices are nearly entirely replaced with microprocessor-based digital protective relays (numerical relays) that emulate their electromechanical ancestors with great precision and convenience in application. By combining several functions in one case, numerical relays also save capital cost and maintenance cost over electromechanical relays. However, due to their very long life span, tens of thousands of these "silent sentinels" are still protecting transmission lines and electrical apparatus all over the world.

Control system

There are two common classes of control systems, with many variations and combinations: logic or sequential controls, and feedback or linear controls. There is also fuzzy logic, which attempts to combine some of the design simplicity of logic with the utility of linear control. Some devices or systems are inherently not controllable.

Overview
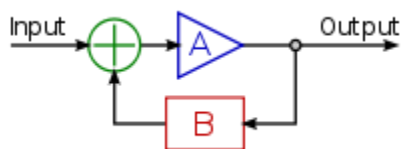
A basic feedback loop

The term "control system" may be applied to the essentially manual controls that allow an operator, for example, to close and open a hydraulic press, perhaps including logic so that it cannot be moved unless safety guards are in place.

An automatic sequential control system may trigger a series of mechanical actuators in the correct sequence to perform a task. For example various electric and pneumatic transducers may fold and glue a cardboard box, fill it with product and then seal it in an automatic packaging machine.

In the case of linear underline feedback systems, a control loop, including sensors, control algorithms and actuators, is arranged in such a fashion as to try to regulate a variable at a setpoint or reference value. An example of this may increase the fuel supply to a furnace when a measured temperature drops. PID controllers are common and effective in cases such as this. Control systems that include some sensing of the results they are trying to achieve are making use of feedback and so can, to some extent, adapt to varying circumstances. Open-loop control systems do not make use of feedback, and run only in pre-arranged ways.

Logic control

Logic control systems for industrial and commercial machinery were historically implemented at mains voltage using interconnected relays, designed using ladder logic. Today, most such systems are constructed with programmable logic controllers (PLCs) or microcontrollers. The notation of ladder logic is still in use as a programming idiom for PLCs. Logic controllers may respond to switches, light sensors, pressure switches, etc., and can cause the machinery to start and stop various operations. Logic systems are used to sequence mechanical operations in many applications. PLC software can be written in many different ways – ladder diagrams, SFC – sequential function charts or in language terms known as statement lists.

Examples include elevators, washing machines and other systems with interrelated stop-go operations.

Logic systems are quite easy to design, and can handle very complex operations. Some aspects of logic system design make use of Boolean logic.

On–off control
For more details on this topic, see Bang–bang control.

For example, a thermostat is a simple negative-feedback control: when the temperature (the "process variable" or PV) goes below a set point (SP), the heater is switched on. Another example could be a pressure switch on an air compressor: when the pressure (PV) drops below the threshold (SP), the pump is powered. Refrigerators and vacuum pumps contain similar mechanisms operating in reverse, but still providing negative feedback to correct errors.

Simple on–off feedback control systems like these are cheap and effective. In some cases, like the simple compressor example, they may represent a good design choice.

In most applications of on–off feedback control, some consideration needs to be given to other costs, such as wear and tear of control valves and maybe other start-up costs when power is reapplied each time the PV drops. Therefore, practical on–off control systems are designed to include hysteresis, usually in the form of a deadband, a region around the setpoint value in which no control action occurs. The width of deadband may be adjustable or programmable.

Linear control

Linear control systems use linear negative feedback to produce a control signal mathematically based on other variables, with a view to maintain the controlled process within an acceptable operating range.

The output from a linear control system into the controlled process may be in the form of a directly variable signal, such as a valve that may be 0 or 100% open or anywhere in between. Sometimes this is not feasible and so, after calculating the current required corrective signal, a linear control system may repeatedly switch an actuator, such as a pump, motor or heater, fully on and then fully off again, regulating the duty cycle using pulse-width modulation.

Proportional control

When controlling the temperature of an industrial furnace, it is usually better to control the opening of the fuel valve in proportion to the current needs of the furnace. This helps avoid thermal shocks and applies heat more effectively.

Proportional negative-feedback systems are based on the difference between the required set point (SP) and process value (PV). This difference is called the error. Power is applied in direct proportion to the current measured error, in the correct sense so as to tend to reduce the error (and so avoid positive feedback). The amount of corrective action that is applied for a given error is set by the gain or sensitivity of the control system.

At low gains, only a small corrective action is applied when errors are detected: the system may be safe and stable, but may be sluggish in response to changing conditions; errors will remain uncorrected for relatively long periods of time: it is over-damped. If the proportional gain is increased, such systems become more responsive and errors are dealt with more quickly. There is an optimal value for the gain setting when the overall system is said to be critically damped. Increases in loop gain beyond this point will lead to oscillations in the PV; such a system is under-damped.

Under-damped furnace example

In the furnace example, suppose the temperature is increasing towards a set point at which, say, 50% of the available power will be required for steady-state. At low temperatures, 100% of available power is applied. When the PV is within, say 10° of the SP the heat input begins to be reduced by the proportional controller. (Note that this implies a 20° "proportional band" (PB) from full to no power input, evenly spread around the setpoint value). At the setpoint the controller will be applying 50% power as required, but stray stored heat within the heater sub-system and in the walls of the furnace will keep the measured temperature rising beyond what is required. At 10° above SP, we reach the top of the proportional band (PB) and no power is applied, but the temperature may continue to rise even further before beginning to fall back. Eventually as the PV falls back into the PB, heat is applied again, but now the heater and the furnace walls are too cool and the temperature falls too low before its fall is arrested, so that the oscillations continue.

Over-damped furnace example

The temperature oscillations that an under-damped furnace control system produces are unacceptable for many reasons, including the waste of fuel and time (each oscillation cycle may take many minutes), as well as the likelihood of seriously overheating both the furnace and its contents.

Suppose that the gain of the control system is reduced drastically and it is restarted. As the temperature approaches, say 30° below SP (60° proportional band or PB now), the heat input begins to be reduced, the rate of heating of the furnace has time to slow and, as the heat is still further reduced, it eventually is brought up to set point, just as 50% power input is reached and the furnace is operating as required. There was some wasted time while the furnace crept to its final temperature using only 52% then 51% of available power, but at least no harm was done. By carefully increasing the gain (i.e. reducing the width of the PB) this over-damped and sluggish behavior can be improved until the system is critically damped for this SP temperature. Doing this is known as 'tuning' the control system. A well-tuned proportional furnace temperature control system will usually be more effective than on-off control, but will still respond more slowly than the furnace could under skillful manual control.

PID control
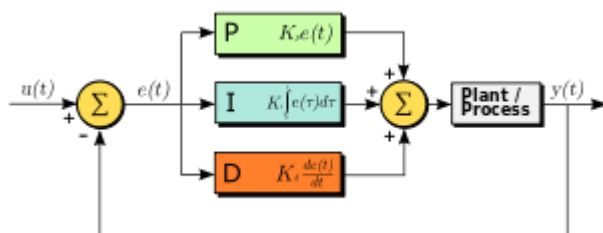
A block diagram of a PID controller
Further information: PID controller

Apart from sluggish performance to avoid oscillations, another problem with proportional-only control is that power application is always in direct proportion to the error. In the example above we assumed that the set temperature could be maintained with 50% power. What happens if the furnace is required in a different application where a higher set temperature will require 80% power to maintain it? If the gain was finally set to a 50° PB, then 80% power will not be applied unless the furnace is 15° below setpoint, so for this other application the operators will have to remember always to set the setpoint temperature 15° higher than actually needed. This 15° figure is not completely constant either: it will depend on the surrounding ambient temperature, as well as other factors that affect heat loss from or absorption within the furnace.

To resolve these two problems, many feedback control schemes include mathematical extensions to improve performance. The most common extensions lead to proportional-integral-derivative control, or PID control (pronounced pee-eye-dee).

Derivative action

The derivative part is concerned with the rate-of-change of the error with time: If the measured variable approaches the setpoint rapidly, then the actuator is backed off early to allow it to coast to the required level; conversely if the measured value begins to move rapidly away from the setpoint, extra effort is applied—in proportion to that rapidity—to try to maintain it.

Derivative action makes a control system behave much more intelligently. On systems like the temperature of a furnace, or perhaps the motion-control of a heavy item like a gun or camera on a moving vehicle, the derivative action of a well-tuned PID controller can allow it to reach and maintain a setpoint better than most skilled human operators could.

If derivative action is over-applied, it can lead to oscillations too. An example would be a PV that increased rapidly towards SP, then halted early and seemed to "shy away" from the setpoint before rising towards it again.

Integral action

The integral term magnifies the effect of long-term steady-state errors, applying ever-increasing effort until they reduce to zero. In the example of the furnace above working at various temperatures, if the heat being applied does not bring the furnace up to setpoint, for whatever reason, integral action increasingly moves the proportional band relative to the setpoint until the PV error is reduced

to zero and the setpoint is achieved.In the furnace example, suppose the temperature is increasing towards a set point at which, say, 50% of the available power will be required for steady-state. At low temperatures, 100% of available power is applied. When the PV is within, say 10° of the SP the heat input begins to be reduced by the proportional controller. (Note that this implies a 20° "proportional band" (PB) from full to no power input, evenly spread around the setpoint value). At the setpoint the controller will be applying 50% power as required, but stray stored heat within the heater sub-system and in the walls of the furnace will keep the measured temperature rising beyond what is required. At 10° above SP, we reach the top of the proportional band (PB) and no power is applied, but the temperature may continue to rise even further before beginning to fall back. Eventually as the PV falls back into the PB, heat is applied again, but now the heater and the furnace walls are too cool and the temperature falls too low before its fall is arrested, so that the oscillations continue.

Other techniques

It is possible to <u>filter</u> the PV or error signal. Doing so can reduce the response of the system to undesirable frequencies, to help reduce instability or oscillations. Some feedback systems will oscillate at just one frequency. By filtering out that frequency, more "stiff" feedback can be applied, making the system more responsive without shaking itself apart.

Feedback systems can be combined. In <u>cascade control</u>, one control loop applies control algorithms to a measured variable against a setpoint, but then provides a varying setpoint to another control loop rather than affecting process variables directly. If a system has several different measured variables to be controlled, separate control systems will be present for each of them.

<u>Control engineering</u> in many applications produces control systems that are more complex than PID control. Examples of such fields include <u>fly-by-wire</u> aircraft control systems, chemical plants, and oil refineries. <u>Model predictive control</u> systems are designed using specialized computer-aided-design software and empirical mathematical models of the system to be controlled.

Fuzzy logic
Further information: <u>Fuzzy logic</u>

<u>Fuzzy logic</u> is an attempt to get the easy design of logic controllers and yet control continuously-varying systems. Basically, a measurement in a fuzzy logic system can be partly true, that is if yes is 1 and no is 0, a fuzzy measurement can be between 0 and 1.

The rules of the system are written in natural language and translated into fuzzy logic. For example, the design for a furnace would start with: "If the temperature

is too high, reduce the fuel to the furnace. If the temperature is too low, increase the fuel to the furnace."

Measurements from the real world (such as the temperature of a furnace) are converted to values between 0 and 1 by seeing where they fall on a triangle. Usually the tip of the triangle is the maximum possible value which translates to "1."

Fuzzy logic, then, modifies Boolean logic to be arithmetical. Usually the "not" operation is "output = 1 - input," the "and" operation is "output = input.1 multiplied by input.2," and "or" is "output = 1 - ((1 - input.1) multiplied by (1 - input.2))". This reduces to Boolean arithmetic if values are restricted to 0 and 1, instead of allowed to range in the unit interval.

The last step is to "defuzzify" an output. Basically, the fuzzy calculations make a value between zero and one. That number is used to select a value on a line whose slope and height converts the fuzzy value to a real-world output number. The number then controls real machinery.

If the triangles are defined correctly and rules are right the result can be a good control system.

When a robust fuzzy design is reduced into a single, quick calculation, it begins to resemble a conventional feedback loop solution and it might appear that the fuzzy design was unnecessary. However, the fuzzy logic paradigm may provide scalability for large control systems where conventional methods become unwieldy or costly to derive.

Fuzzy electronics is an electronic technology that uses fuzzy logic instead of the two-value logic more commonly used in digital electronics.

Physical implementations

Since modern small microprocessors are so cheap (often less than $1 US), it's very common to implement control systems, including feedback loops, with computers, often in an embedded system. The feedback controls are simulated by having the computer make periodic measurements and then calculating from this stream of measurements (see digital signal processing, sampled data systems).

Computers emulate logic devices by making measurements of switch inputs, calculating a logic function from these measurements and then sending the results out to electronically-controlled switches.

Logic systems and feedback controllers are usually implemented with programmable logic controllers which are devices available from electrical supply houses. They include a little computer and a simplified system for programming. Most often they are programmed with personal computers.

A control system is a device or set of devices to manage, command, direct or regulate the behavior of other devices or systems. A control mechanism is a process used by a control system.

Motion control

Motion control is a sub-field of automation, in which the position or velocity of machines are controlled using some type of device such as a hydraulic pump, linear actuator, or an electric motor, generally a servo. Motion control is an important part of robotics and CNC machine tools, however it is more complex than in the use of specialized machines, where the kinematics are usually simpler. The latter is often called General Motion Control (GMC). Motion control is widely used in the packaging, printing, textile, semiconductor production, and assembly industries.

Overview

The basic architecture of a motion control system contains:

- A motion controller to generate set points (the desired output or motion profile) and close a position or velocity feedback loop. A drive or amplifier to transform the control signal from the motion controller into a higher power electrical current or voltage that is presented to the actuator. Newer "intelligent" drives can close the position and velocity loops internally, resulting in much more accurate control.

- An actuator such as a hydraulic pump, air cylinder, linear actuator, or electric motor for output motion.
- One or more feedback sensors such as optical encoders, resolvers or Hall effect devices to return the position or velocity of the actuator to the motion controller in order to close the position or velocity control loops.
- Mechanical components to transform the motion of the actuator into the desired motion, including: gears, shafting, ball screw, belts, linkages, and linear and rotational bearings.

The interface between the motion controller and drives it controls is very critical when coordinated motion is required, as it must provide tight synchronization. Historically the only open interface was an analog signal, until open interfaces were developed that

satisfied the requirements of coordinated motion control, the first being <u>SERCOS</u> in 1991 which is now enhanced to <u>SERCOS III</u>. Later interfaces capable of motion control include <u>Ethernet/IP</u>, <u>Profinet IRT</u>, <u>Ethernet Powerlink</u>, and <u>EtherCAT</u>.

Common control functions include:

- Velocity control.
- Position (point-to-point) control: There are several methods for computing a motion trajectory. These are often based on the velocity profiles of a move such as a triangular profile, trapezoidal profile, or an S-curve profile.
- Pressure or Force control.
- Electronic gearing (or cam profiling): The position of a slave axis is mathematically linked to the position of a master axis. A good example of this would be in a system where two rotating drums turn at a given ratio to each other. A more advanced case of electronic gearing is electronic camming. With electronic camming, a slave axis follows a profile that is a function of the master position. This profile need not be salted, but it must be an animated <u>function</u>.

Voltage source

In electric <u>circuit theory</u>, an ideal voltage source is a circuit element where the voltage across it is independent of the current through it. A voltage source is the <u>dual</u> of a <u>current source</u>. In analysis, a voltage source supplies a constant DC or AC potential between its terminals for any current flow through it. Real-world sources of electrical energy, such as batteries, generators, or power systems, can be modeled for analysis purposes as a combination of an ideal voltage source and additional combinations of <u>impedance</u> elements.
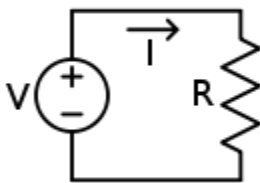
A schematic diagram of an ideal voltage source, V, driving a resistor, R, and creating a current I

Ideal voltage sources

An ideal voltage source is a mathematical abstraction that simplifies the analysis of electric circuits. If the voltage across an ideal voltage source can be specified independently of any other variable in a circuit, it is called an independent voltage source. Conversely, if the voltage across an ideal voltage source is determined by some other voltage or current in a circuit, it is called a dependent or controlled voltage source. A

mathematical model of an amplifier will include dependent voltage sources whose magnitude is governed by some fixed relation to an input signal, for example. In the analysis of <u>faults on electrical power systems</u>, the whole network of interconnected sources and transmission lines can be usefully replaced by an ideal (AC) voltage source and a single equivalent impedance.

Voltage Source   <u>Current Source</u>

Controlled Voltage Source   Controlled Current Source

<u>Battery</u> of cells   Single cell

Symbols used for voltage sources

The <u>internal resistance</u> of an ideal voltage source is zero; it is able to supply or absorb any amount of current. The current through an ideal voltage source is completely determined by the external circuit. When connected to an open circuit, there is zero current and thus zero power. When connected to a <u>load resistance</u>, the current through the source approaches infinity as the load resistance approaches zero (a short circuit). Thus, an ideal voltage source can supply unlimited power.

No real voltage source is ideal; all have a non-zero effective internal resistance, and none can supply unlimited current. However, the internal resistance of a real voltage source is effectively modeled in linear circuit analysis by combining a non-zero resistance in series with an ideal voltage source.

Comparison between voltage and current sources

Most sources of electrical energy (the <u>mains</u>, a <u>battery</u>) are modeled as voltage sources. An ideal voltage source provides no energy when it is loaded by an <u>open circuit</u> (i.e. an infinite <u>impedance</u>), but approaches infinite energy and current when the <u>load resistance</u> approaches zero (a <u>short circuit</u>). Such a theoretical device would have a zero <u>ohm</u> <u>output</u>

impedance in series with the source. A real-world voltage source has a very low, but non-zero output impedance: often much less than 1 ohm.

Conversely, a current source provides a constant current, as long as the load connected to the source terminals has sufficiently low impedance. An ideal current source would provide no energy to a short circuit and approach infinite energy and voltage as the load resistance approaches infinity (an open circuit). An ideal current source has an infinite output impedance in parallel with the source. A real-world current source has a very high, but finite output impedance. In the case of transistor current sources, impedance of a few megohms (at low frequencies) is typical.

Since no ideal sources of either variety exist (all real-world examples have finite and non-zero source impedance), any current source can be considered as a voltage source with the same source impedance and vice versa. Voltage sources and current sources are sometimes said to be duals of each other and any non ideal source can be converted from one to the other by applying Norton's or Thevenin's theorems.

Network analysis (electrical circuits)

A network, in the context of electronics, is a collection of interconnected components. Network analysis is the process of finding the voltages across, and the currents through, every component in the network. There are a number of different techniques for achieving this. However, for the most part, they assume that the components of the network are all linear. The methods described in this article are only applicable to linear network analysis except where explicitly stated.

Component	A device with two or more terminals into which, or out of which, charge may flow.
Node	A point at which terminals of more than two components are joined. A conductor with a substantially zero resistance is considered to be a node for the purpose of analysis.
Branch	The component(s) joining two nodes.
Mesh	A group of branches within a network joined so as to form a complete loop.
Port	Two terminals where the current into one is identical to the current out of the other.
Circuit	A current from one terminal of a generator, through load component(s) and back into the other terminal. A circuit is, in this sense, a one-port network and is a trivial case to analyse. If there is any connection to any other circuits then a non-trivial network has been formed and at least two ports must exist. Often, "circuit" and "network" are used interchangeably, but many analysts reserve "network" to mean an idealised model consisting of ideal components.
Transfer function	The relationship of the currents and/or voltages between two ports. Most often, an input port and an output port are discussed and the transfer

	function is described as gain or attenuation.
Component transfer function	For a two-terminal component (i.e. one-port component), the current and voltage are taken as the input and output and the transfer function will have units of impedance or admittance (it is usually a matter of arbitrary convenience whether voltage or current is considered the input). A three (or more) terminal component effectively has two (or more) ports and the transfer function cannot be expressed as a single impedance. The usual approach is to express the transfer function as a matrix of parameters. These parameters can be impedances, but there is a large number of other approaches, see two-port network.

Equivalent circuits
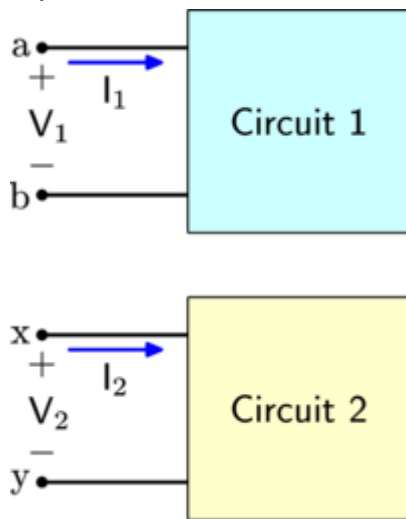
A useful procedure in network analysis is to simplify the network by reducing the number of components. This can be done by replacing the actual components with other notional components that have the same effect. A particular technique might directly reduce the number of components, for instance by combining impedances in series. On the other hand it might merely change the form in to one in which the components can be reduced in a later operation. For instance, one might transform a voltage generator into a current generator using Norton's theorem in order to be able to later combine the internal resistance of the generator with a parallel impedance load.

A resistive circuit is a circuit containing only resistors, ideal current sources, and ideal voltage sources. If the sources are constant (DC) sources, the result is a DC circuit. The analysis of a circuit refers to the process of solving for the voltages and currents present in the circuit. The solution principles outlined here also apply to phasor analysis of AC circuits.

Two circuits are said to be equivalent with respect to a pair of terminals if the voltage across the terminals and current through the terminals for one network have the same relationship as the voltage and current at the terminals of the other network.

If $V_2 = V_1$ implies $I_2 = I_1$ for all (real) values of V_1, then with respect to terminals ab and xy, circuit 1 and circuit 2 are equivalent.

The above is a sufficient definition for a one-port network. For more than one port, then it must be defined that the currents and voltages between all pairs of corresponding ports must bear the same relationship. For instance, star and delta networks are effectively three port networks and hence require three simultaneous equations to fully specify their equivalence.

Impedances in series and in parallel

Any two terminal network of impedances can eventually be reduced to a single impedance by successive applications of impedances in series or impedances in parallel.

Impedances in <u>series</u>: $Z_{eq} = Z_1 + Z_2 + \cdots + Z_n.$

Impedances in <u>parallel</u>: $\dfrac{1}{Z_{eq}} = \dfrac{1}{Z_1} + \dfrac{1}{Z_2} + \cdots + \dfrac{1}{Z_n}.$

The above simplified for only two impedances in parallel: $Z_{eq} = \dfrac{Z_1 Z_2}{Z_1 + Z_2}.$

Delta-wye transformation

Main article: <u>Y-Δ transform</u>

"Delta"   "Star"
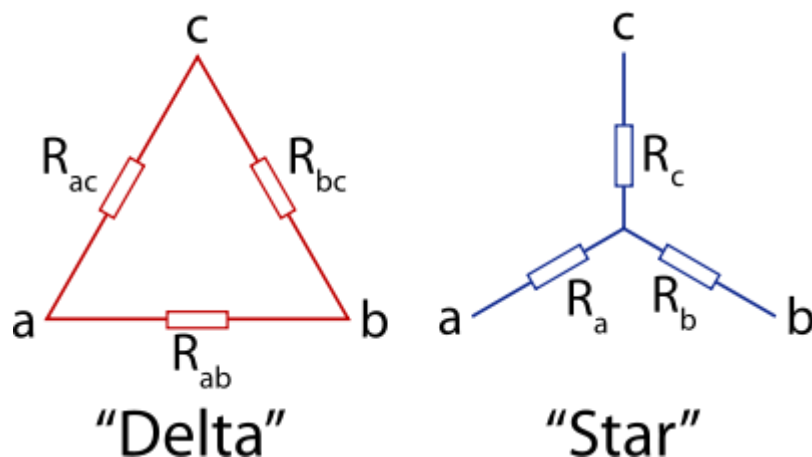
A network of impedances with more than two terminals cannot be reduced to a single impedance equivalent circuit. An n-terminal network can, at best, be reduced to n impedances (at worst nC2). For a three terminal network, the three impedances can be expressed as a three node delta (Δ) network or four node star (Y) network. These two

networks are equivalent and the transformations between them are given below. A general network with an arbitrary number of nodes cannot be reduced to the minimum number of impedances using only series and parallel combinations. In general, Y-Δ and Δ-Y transformations must also be used. For some networks the extension of Y-Δ to star-polygon transformations may also be required.

For equivalence, the impedances between any pair of terminals must be the same for both networks, resulting in a set of three simultaneous equations. The equations below are expressed as resistances but apply equally to the general case with impedances.

Delta-to-star transformation equations

$$R_a = \frac{R_{ac}R_{ab}}{R_{ac} + R_{ab} + R_{bc}}$$

$$R_b = \frac{R_{ab}R_{bc}}{R_{ac} + R_{ab} + R_{bc}}$$

$$R_c = \frac{R_{bc}R_{ac}}{R_{ac} + R_{ab} + R_{bc}}$$

Star-to-delta transformation equations

$$R_{ac} = \frac{R_aR_b + R_bR_c + R_cR_a}{R_b}$$

$$R_{ab} = \frac{R_aR_b + R_bR_c + R_cR_a}{R_c}$$

$$R_{bc} = \frac{R_aR_b + R_bR_c + R_cR_a}{R_a}$$

General form of network node elimination

The star-to-delta and series-resistor transformations are special cases of the general resistor network node elimination algorithm. Any node connected by N resistors (R_1 .. R_N) to nodes 1 .. N can be replaced by $\binom{N}{2}$ resistors interconnecting the remaining N nodes. The resistance between any two nodes x and y is given by:

$$R_{xy} = R_x R_y \sum_{i=1}^{N} \frac{1}{R_i}$$

For a star-to-delta ($N = 3$) this reduces to:

$$R_{ab} = R_a R_b \left(\frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_c} \right) = \frac{R_a R_b (R_a R_b + R_a R_c + R_b R_c)}{R_a R_b R_c} = \frac{R_a R_b + R_b R_c}{R_c}$$

For a series reduction ($N = 2$) this reduces to:

$$R_{ab} = R_a R_b \left(\frac{1}{R_a} + \frac{1}{R_b}\right) = \frac{R_a R_b (R_a + R_b)}{R_a R_b} = R_a + R_b$$

For a dangling resistor ($N = 1$) it results in the elimination of the resistor because $\binom{1}{2} = 0$.

Source transformation
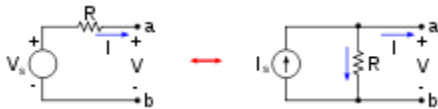
A generator with an internal impedance (i.e. non-ideal generator) can be represented as either an ideal voltage generator or an ideal current generator plus the impedance. These two forms are equivalent and the transformations are given below. If the two networks are equivalent with respect to terminals ab, then V and I must be identical for both networks. Thus,

$$V_s = R I_s \text{or} \quad I_s = \frac{V_s}{R}$$

- Norton's theorem states that any two-terminal network can be reduced to an ideal current generator and a parallel impedance.
- Thévenin's theorem states that any two-terminal network can be reduced to an ideal voltage generator plus a series impedance.

Simple networks

Some very simple networks can be analysed without the need to apply the more systematic approaches.

Voltage division of series components

Consider n impedances that are connected in series. The voltage V_i across any impedance Z_i is

$$V_i = Z_i I = \left(\frac{Z_i}{Z_1 + Z_2 + \cdots + Z_n}\right) V$$

Current division of parallel components

Consider n impedances that are connected in parallel. The current I_i through any impedance Z_i is

$$I_i = \left(\frac{\left(\frac{1}{Z_i} \right)}{\left(\frac{1}{Z_1} \right) + \left(\frac{1}{Z_2} \right) + \cdots + \left(\frac{1}{Z_n} \right)} \right) I$$

for $i = 1, 2, ..., n.$

Special case: Current division of two parallel components

$$I_1 = \left(\frac{Z_2}{Z_1 + Z_2} \right) I$$
$$I_2 = \left(\frac{Z_1}{Z_1 + Z_2} \right) I$$

Nodal analysis

1. Label all nodes in the circuit. Arbitrarily select any node as reference.

2. Define a voltage variable from every remaining node to the reference. These voltage variables must be defined as voltage rises with respect to the reference node.

3. Write a KCL equation for every node except the reference.

4. Solve the resulting system of equations.

Mesh analysis

Mesh — a loop that does not contain an inner loop.

1. Count the number of "window panes" in the circuit. Assign a mesh current to each window pane.

2. Write a KVL equation for every mesh whose current is unknown.

3. Solve the resulting equations

Superposition
Main article: Superposition theorem

In this method, the effect of each generator in turn is calculated. All the generators other than the one being considered are removed; either short-circuited in the case of voltage generators, or open circuited in the case of current generators. The total current through,

or the total voltage across, a particular branch is then calculated by summing all the individual currents or voltages.

There is an underlying assumption to this method that the total current or voltage is a linear superposition of its parts. The method cannot, therefore, be used if non-linear components are present. Note that mesh analysis and node analysis also implicitly use superposition so these too, are only applicable to linear circuits.

[Choice of method

Choice of method is to some extent a matter of taste. If the network is particularly simple or only a specific current or voltage is required then ad-hoc application of some simple equivalent circuits may yield the answer without recourse to the more systematic methods.

- Superposition is possibly the most conceptually simple method but rapidly leads to a large number of equations and messy impedance combinations as the network becomes larger.
- Nodal analysis: The number of voltage variables, and hence simultaneous equations to solve, equals the number of nodes minus one. Every voltage source connected to the reference node reduces the number of unknowns (and equations) by one.
- Mesh analysis: The number of current variables, and hence simultaneous equations to solve, equals the number of meshes. Every current source in a mesh reduces the number of unknowns by one. Mesh analysis can only be used with networks which can be drawn as a planar network, that is, with no crossing components. Transfer function

A transfer function expresses the relationship between an input and an output of a network. For resistive networks, this will always be a simple real number or an expression which boils down to a real number. Resistive networks are represented by a system of simultaneous algebraic equations. However in the general case of linear networks, the network is represented by a system of simultaneous linear differential equations. In network analysis, rather than use the differential equations directly, it is usual practice to carry out a Laplace transform on them first and then express the result in terms of the Laplace parameter s, which in general is complex. This is described as working in the s-domain. Working with the equations directly would be described as working in the time (or t) domain because the results would be expressed as time varying quantities. The Laplace transform is the mathematical method of transforming between the s-domain and the t-domain.

This approach is standard in control theory and is useful for determining stability of a system, for instance, in an amplifier with feedback.

Two terminal component transfer functions

For two terminal components the transfer function, otherwise called the <u>constitutive</u> <u>equation</u>, is the relationship between the current input to the device and the resulting voltage across it. The transfer function, Z(s), will thus have units of impedance - ohms. For the three passive components found in electrical networks, the transfer functions are;

Resistor $\quad Z(s) = R$

Inductor $\quad Z(s) = sL$

Capacitor $Z(s) = \dfrac{1}{sC}$

For a network to which only steady ac signals are applied, s is replaced with jω and the more familiar values from ac network theory result.

Resistor $\quad Z(j\omega) = R$

Inductor $\quad Z(j\omega) = j\omega L$

Capacitor $Z(j\omega) = \dfrac{1}{j\omega C}$

Finally, for a network to which only steady dc is applied, s is replaced with zero and dc network theory applies.

Resistor $\quad Z = R$

Inductor $\quad Z = 0$

Capacitor $Z = \infty$

Two port network transfer function

Transfer functions, in general, in control theory are given the symbol H(s). Most commonly in electronics, transfer function is defined as the ratio of output voltage to input voltage and given the symbol A(s), or more commonly (because analysis is invariably done in terms of sine wave response), A(jω), so that;

$$A(j\omega) = \frac{V_o}{V_i}$$

The A standing for attenuation, or amplification, depending on context. In general, this will be a complex function of jω, which can be derived from an analysis of the impedances in the network and their individual transfer functions. Sometimes the analyst is only interested in the magnitude of the gain and not the phase angle. In this case the complex numbers can be eliminated from the transfer function and it might then be written as;

$$A(\omega) = \left| \frac{V_o}{V_i} \right|$$

Two port parameters

The concept of a two-port network can be useful in network analysis as a black box approach to analysis. The behaviour of the two-port network in a larger network can be entirely characterised without necessarily stating anything about the internal structure. However, to do this it is necessary to have more information than just the A(jω) described above. It can be shown that four such parameters are required to fully characterise the two-port network. These could be the forward transfer function, the input impedance, the reverse transfer function (i.e., the voltage appearing at the input when a voltage is applied to the output) and the output impedance. There are many others (see the main article for a full listing), one of these expresses all four parameters as impedances. It is usual to express the four parameters as a matrix;

$$\begin{bmatrix} V_1 \\ V_0 \end{bmatrix} = \begin{bmatrix} z(j\omega)_{11} & z(j\omega)_{12} \\ z(j\omega)_{21} & z(j\omega)_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_0 \end{bmatrix}$$

The matrix may be abbreviated to a representative element;

$[z(j\omega)]_{\text{or just}} [z]$

These concepts are capable of being extended to networks of more than two ports. However, this is rarely done in reality as in many practical cases ports are considered either purely input or purely output. If reverse direction transfer functions are ignored, a multi-port network can always be decomposed into a number of two-port networks.

Distributed components

Where a network is composed of discrete components, analysis using two-port networks is a matter of choice, not essential. The network can always alternatively be analysed in terms of its individual component transfer functions. However, if a network contains distributed components, such as in the case of a transmission line, then it is not possible to analyse in terms of individual components since they do not exist. The most common approach to this is to model the line as a two-port network and characterise it using two-port parameters (or something equivalent to them). Another example of this technique is modelling the carriers crossing the base region in a high frequency transistor. The base region has to be modelled as distributed resistance and capacitance rather than lumped components.

Image analysis

Transmission lines and certain types of filter design use the image method to determine their transfer parameters. In this method, the behaviour of an infinitely long cascade

connected chain of identical networks is considered. The input and output impedances and the forward and reverse transmission functions are then calculated for this infinitely long chain. Although the theoretical values so obtained can never be exactly realised in practice, in many cases they serve as a very good approximation for the behaviour of a finite chain as long as it is not too short.

Non-linear networks

Most electronic designs are, in reality, non-linear. There is very little that does not include some semiconductor devices. These are invariably non-linear, the transfer function of an ideal semiconductor pn junction is given by the very non-linear relationship;

$$i = I_o(e^{\frac{v}{V_T}} - 1)$$

where;

- i and v are the instantaneous current and voltage.
- Io is an arbitrary parameter called the reverse leakage current whose value depends on the construction of the device.
- VT is a parameter proportional to temperature called the thermal voltage and equal to about 25mV at room temperature.

There are many other ways that non-linearity can appear in a network. All methods utilising linear superposition will fail when non-linear components are present. There are several options for dealing with non-linearity depending on the type of circuit and the information the analyst wishes to obtain.

Constitutive equations

The diode equation above is an example of a <u>constitutive equation</u> of the general form,

$$f(v, i) = 0$$

This can be thought of as a non-linear resistor. The corresponding constitutive equations for non-linear inductors and capacitors are respectively;

$$f(v, \varphi) = 0$$
$$f(v, q) = 0$$

where f is any arbitrary function, φ is the stored magnetic flux and q is the stored charge.

Existence, uniqueness and stability

An important consideration in non-linear analysis is the question of uniqueness. For a network composed of linear components there will always be one, and only one, unique solution for a given set of boundary conditions. This is not always the case in non-linear circuits. For instance, a linear resistor with a fixed voltage applied to it has only one solution for the current through it. On the other hand, the non-linear tunnel diode has up to three solutions for the current for a given voltage. That is, a particular solution for the current through the diode is not unique, there may be others, equally valid. In some cases there may not be a solution at all: the question of existence of solutions must be considered.

Another important consideration is the question of stability. A particular solution may exist, but it may not be stable, rapidly departing from that point at the slightest stimulation. It can be shown that a network that is absolutely stable for all conditions must have one, and only one, solution for each set of conditions.[4]

Methods

Boolean analysis of switching networks

A switching device is one where the non-linearity is utilised to produce two opposite states. CMOS devices in digital circuits, for instance, have their output connected to either the positive or the negative supply rail and are never found at anything in between except during a transient period when the device is actually switching. Here the non-linearity is designed to be extreme, and the analyst can actually take advantage of that fact. These kinds of networks can be analysed using Boolean algebra by assigning the two states ("on"/"off", "positive"/"negative" or whatever states are being used) to the boolean constants "0" and "1".

The transients are ignored in this analysis, along with any slight discrepancy between the actual state of the device and the nominal state assigned to a boolean value. For instance, boolean "1" may be assigned to the state of +5V. The output of the device may actually be +4.5V but the analyst still considers this to be boolean "1". Device manufacturers will usually specify a range of values in their data sheets that are to be considered undefined (i.e. the result will be unpredictable).

The transients are not entirely uninteresting to the analyst. The maximum rate of switching is determined by the speed of transition from one state to the other. Happily for the analyst, for many devices most of the transition occurs in the linear portion of the devices transfer function and linear analysis can be applied to obtain at least an approximate answer.

It is mathematically possible to derive boolean algebras which have more than two states. There is not too much use found for these in electronics, although three-state devices are passingly common.

Separation of bias and signal analyses

This technique is used where the operation of the circuit is to be essentially linear, but the devices used to implement it are non-linear. A transistor amplifier is an example of this kind of network. The essence of this technique is to separate the analysis in to two parts. Firstly, the dc biases are analysed using some non-linear method. This establishes the quiescent operating point of the circuit. Secondly, the small signal characteristics of the circuit are analysed using linear network analysis. Examples of methods that can be used for both these stages are given below.

Graphical method of dc analysis

In a great many circuit designs, the dc bias is fed to a non-linear component via a resistor (or possibly a network of resistors). Since resistors are linear components, it is particularly easy to determine the quiescent operating point of the non-linear device from a graph of its transfer function. The method is as follows: from linear network analysis the output transfer function (that is output voltage against output current) is calculated for the network of resistor(s) and the generator driving them. This will be a straight line and can readily be superimposed on the transfer function plot of the non-linear device. The point where the lines cross is the quiescent operating point.

Perhaps the easiest practical method is to calculate the (linear) network open circuit voltage and short circuit current and plot these on the transfer function of the non-linear device. The straight line joining these two point is the transfer function of the network.

In reality, the designer of the circuit would proceed in the reverse direction to that described. Starting from a plot provided in the manufacturers data sheet for the non-linear device, the designer would choose the desired operating point and then calculate the linear component values required to achieve it.

It is still possible to use this method if the device being biased has its bias fed through another device which is itself non-linear - a diode for instance. In this case however, the plot of the network transfer function onto the device being biased would no longer be a straight line and is consequently more tedious to do.

Small signal equivalent circuit

This method can be used where the deviation of the input and output signals in a network stay within a substantially linear portion of the non-linear devices transfer function, or else are so small that the curve of the transfer function can be considered linear. Under a set of these specific conditions, the non-linear device can be represented by an equivalent linear network. It must be remembered that this equivalent circuit is entirely notional and only valid for the small signal deviations. It is entirely inapplicable to the dc biasing of the device.

For a simple two-terminal device, the small signal equivalent circuit may be no more than two components. A resistance equal to the slope of the v/i curve at the operating point (called the dynamic resistance), and tangent to the curve. A generator, because this tangent will not, in general, pass through the origin. With more terminals, more complicated equivalent circuits are required.

A popular form of specifying the small signal equivalent circuit amongst transistor manufacturers is to use the two-port network parameters known as [h] parameters. These are a matrix of four parameters as with the [z] parameters but in the case of the [h] parameters they are a hybrid mixture of impedances, admittances, current gains and voltage gains. In this model the three terminal transistor is considered to be a two port network, one of its terminals being common to both ports. The [h] parameters are quite different depending on which terminal is chosen as the common one. The most important parameter for transistors is usually the forward current gain, h21, in the common emitter configuration. This is designated hfe on data sheets.

The small signal equivalent circuit in terms of two-port parameters leads to the concept of dependent generators. That is, the value of a voltage or current generator depends linearly on a voltage or current elsewhere in the circuit. For instance the [z] parameter model leads to dependent voltage generators as shown in this diagram;
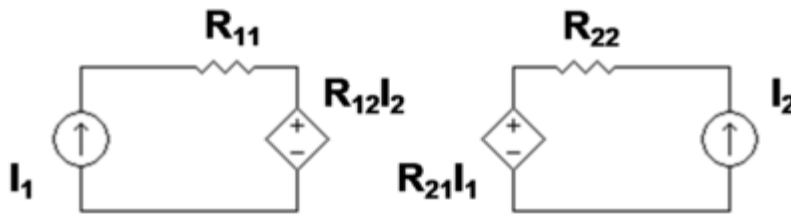
[z] parameter equivalent circuit showing dependent voltage generators

There will always be dependent generators in a two-port parameter equivalent circuit. This applies to the [h] parameters as well as to the [z] and any other kind. These dependencies must be preserved when developing the equations in a larger linear network analysis.

Piecewise linear method

In this method, the transfer function of the non-linear device is broken up into regions. Each of these regions is approximated by a straight line. Thus, the transfer function will be linear up to a particular point where there will be a discontinuity. Past this point the transfer function will again be linear but with a different slope.

A well known application of this method is the approximation of the transfer function of a pn junction diode. The actual transfer function of an ideal diode has been given at the top of this (non-linear) section. However, this formula is rarely used in network analysis, a piecewise approximation being used instead. It can be seen that the diode current

rapidly diminishes to -Io as the voltage falls. This current, for most purposes, is so small it can be ignored. With increasing voltage, the current increases exponentially. The diode is modelled as an open circuit up to the knee of the exponential curve, then past this point as a resistor equal to the bulk resistance of the semiconducting material.

The commonly accepted values for the transition point voltage are 0.7V for silicon devices and 0.3V for germanium devices. An even simpler model of the diode, sometimes used in switching applications, is short circuit for forward voltages and open circuit for reverse voltages.

The model of a forward biased pn junction having an approximately constant 0.7V is also a much used approximation for transistor base-emitter junction voltage in amplifier design.

The piecewise method is similar to the small signal method in that linear network analysis techniques can only be applied if the signal stays within certain bounds. If the signal crosses a discontinuity point then the model is no longer valid for linear analysis purposes. The model does have the advantage over small signal however, in that it is equally applicable to signal and dc bias. These can therefore both be analysed in the same operations and will be linearly superimposable.

Time-varying components

In linear analysis, the components of the network are assumed to be unchanging, but in some circuits this does not apply, such as sweep oscillators, voltage controlled amplifiers, and variable equalisers. In many circumstances the change in component value is periodic. A non-linear component excited with a periodic signal, for instance, can be represented as periodically varying linear component. Sidney Darlington disclosed a method of analysing such periodic time varying circuits. He developed canonical circuit forms which are analogous to the canonical forms of Ronald Foster and Wilhelm Cauer used for analysing linear circuits

Electricity is the science, engineering, technology and physical phenomena associated with the presence and flow of electric charges. Electricity gives a wide variety of well-known electrical effects, such as lightning, static electricity, electromagnetic induction and the flow of electrical current in an electrical wire. In addition, electricity permits the creation and reception of electromagnetic radiation such as radio waves.

In electricity, charges produce electromagnetic fields which act on other charges. Electricity occurs due to several types of physics:

- Electric charge: a property of some subatomic particles, which determines their electromagnetic interactions. Electrically charged matter is influenced by, and produces, electromagnetic fields.
- Electric current: a movement or flow of electrically charged particles, typically measured in amperes.

- Electric field (see electrostatics): an especially simple type of electromagnetic field produced by an electric charge even when it is not moving (i.e., there is no electric current). The electric field produces a force on other charges in its vicinity. Moving charges additionally produce a magnetic field.
- Electric potential: the capacity of an electric field to do work on an electric charge, typically measured in volts.
- Electromagnets: electrical currents generate magnetic fields, and changing magnetic fields generate electrical currents

In electrical engineering, electricity is used for:

- electric power (which can refer imprecisely to a quantity of electrical potential energy or else more correctly to electrical energy per time) that is provided commercially, by the electrical power industry. In a loose but common use of the term, "electricity" may be used to mean "wired for electricity" which means a working connection to an electric power station. Such a connection grants the user of "electricity" access to the electric field present in electrical wiring, and thus to electric power.
- electronics which deals with electrical circuits that involve active electrical components such as vacuum tubes, transistors, diodes and integrated circuits, and associated passive interconnection technologies.

Electric charge is a property of certain subatomic particles, which gives rise to and interacts with the electromagnetic force, one of the four fundamental forces of nature. Charge originates in the atom, in which its most familiar carriers are the electron and proton. It is a conserved quantity, that is, the net charge within an isolated system will always remain constant regardless of any changes taking place within that system. Within the system, charge may be transferred between bodies, either by direct contact, or by passing along a conducting material, such as a wire.

Electric current

The movement of electric charge is known as an electric current, the intensity of which is usually measured in amperes. Current can consist of any moving charged particles; most commonly these are electrons, but any charge in motion constitutes a current.

Electric field; Electrostatics.

The concept of the electric field was introduced by Michael Faraday. An electric field is created by a charged body in the space that surrounds it, and results in a force exerted on

any other charges placed within the field. The electric field acts between two charges in a similar manner to the way that the gravitational field acts between two <u>masses</u>, and like it, extends towards infinity and shows an inverse square relationship with distance. However, there is an important difference. Gravity always acts in attraction, drawing two masses together, while the electric field can result in either attraction or repulsion. Since large bodies such as planets generally carry no net charge, the electric field at a distance is usually zero. Thus gravity is the dominant force at distance in the universe, despite being much weaker. An electric field generally varies in space, and its strength at any one point is defined as the force (per unit charge) that would be felt by a stationary, negligible charge if placed at that point. The conceptual charge, termed a '<u>test charge</u>', must be vanishingly small to prevent its own electric field disturbing the main field and must also be stationary to prevent the effect of <u>magnetic fields</u>. As the electric field is defined in terms of <u>force</u>, and force is a <u>vector</u>, so it follows that an electric field is also a vector, having both <u>magnitude</u> and <u>direction</u>. Specifically, it is a <u>vector field</u>. The study of electric fields created by stationary charges is called <u>electrostatics</u>. The field may be visualized by a set of imaginary lines whose direction at any point is the same as that of the field. This concept was introduced by Faraday, whose term '<u>lines of force</u>' still sometimes sees use. The field lines are the paths that a point positive charge would seek to make as it was forced to move within the field; they are however an imaginary concept with no physical existence, and the field permeates all the intervening space between the lines. Field lines emanating from stationary charges have several key properties: first, that they originate at positive charges and terminate at negative charges; second, that they must enter any good conductor at right angles, and third, that they may never cross nor close in on themselves. A hollow conducting body carries all its charge on its outer surface. The field is therefore zero at all places inside the body. This is the operating principal of the <u>Faraday cage</u>, a conducting metal shell which isolates its interior from outside electrical effects.

The principles of electrostatics are important when designing items of <u>high-voltage</u> equipment. There is a finite limit to the electric field strength that may be withstood by any medium. Beyond this point, <u>electrical breakdown</u> occurs and an <u>electric arc</u> causes flashover between the charged parts. Air, for example, tends to arc across small gaps at electric field strengths which exceed 30 kV per centimeter. Over larger gaps, its breakdown strength is weaker, perhaps 1 kV per centimeter. The most visible natural occurrence of this is <u>lightning</u>, caused when charge becomes separated in the clouds by rising columns of air, and raises the electric field in the air to greater than it can withstand. The voltage of a large lightning cloud may be as high as 100 MV and have discharge energies as great as 250 kWh.

Electric potential

The concept of electric potential is closely linked to that of the electric field. A small charge placed within an electric field experiences a force, and to have brought that charge to that point against the force requires <u>work</u>. The electric potential at any point is defined as the energy required to bring a unit test charge from an <u>infinite distance</u> slowly to that point. It is usually measured in <u>volts</u>, and one volt is the potential for which one <u>joule</u> of

work must be expended to bring a charge of one coulomb from infinity. This definition of potential, while formal, has little practical application, and a more useful concept is that of electric potential difference, and is the energy required to move a unit charge between two specified points. An electric field has the special property that it is conservative, which means that the path taken by the test charge is irrelevant: all paths between two specified points expend the same energy, and thus a unique value for potential difference may be stated. The volt is so strongly identified as the unit of choice for measurement and description of electric potential difference that the term voltage sees greater everyday usage.

For practical purposes, it is useful to define a common reference point to which potentials may be expressed and compared. While this could be at infinity, a much more useful reference is the Earth itself, which is assumed to be at the same potential everywhere. This reference point naturally takes the name earth or ground. Earth is assumed to be an infinite source of equal amounts of positive and negative charge, and is therefore electrically uncharged—and unchargeable.

Electric potential is a scalar quantity, that is, it has only magnitude and not direction. It may be viewed as analogous to height: just as a released object will fall through a difference in heights caused by a gravitational field, so a charge will 'fall' across the voltage caused by an electric field. As relief maps show contour lines marking points of equal height, a set of lines marking points of equal potential (known as equipotentials) may be drawn around an electrostatically charged object. The equipotentials cross all lines of force at right angles. They must also lie parallel to a conductor's surface, otherwise this would produce a force that will move the charge carriers to even the potential of the surface. The electric field was formally defined as the force exerted per unit charge, but the concept of potential allows for a more useful and equivalent definition: the electric field is the local gradient of the electric potential. Usually expressed in volts per meter, the vector direction of the field is the line of greatest slope of potential, and where the equipotentials lie closest together.

Electromagnets; This relationship between magnetic fields and currents is extremely important, for it led to Michael Faraday's invention of the electric motor in 1821. Faraday's homopolar motor consisted of a permanent magnet sitting in a pool of mercury. A current was allowed through a wire suspended from a pivot above the magnet and dipped into the mercury. The magnet exerted a tangential force on the wire, making it circle around the magnet for as long as the current was maintained. Experimentation by Faraday in 1831 revealed that a wire moving perpendicular to a magnetic field developed a potential difference between its ends. Further analysis of this process, known as electromagnetic induction, enabled him to state the principle, now known as Faraday's law of induction, that the potential difference induced in a closed circuit is proportional to the rate of change of magnetic flux through the loop. Exploitation of this discovery enabled him to invent the first electrical generator in 1831, in which he converted the mechanical energy of a rotating copper disc to electrical energy. Faraday's disc was inefficient and of no use as a practical generator, but it showed the possibility of generating electric power using magnetism, a possibility that would be taken up by those

that followed on from his work. Faraday's and Ampère's work showed that a time-varying magnetic field acted as a source of an electric field, and a time-varying electric field was a source of a magnetic field. Thus, when either field is changing in time, then a field of the other is necessarily induced. Such a phenomenon has the properties of a wave, and is naturally referred to as an electromagnetic wave. Electromagnetic waves were analyzed theoretically by James Clerk Maxwell in 1864. Maxwell developed a set of equations that could unambiguously describe the interrelationship between electric field, magnetic field, electric charge, and electric current. He could moreover prove that such a wave would necessarily travel at the speed of light, and thus light itself was a form of electromagnetic radiation. Maxwell's Laws, which unify light, fields, and charge are one of the great milestones of theoretical physics. Electric circuits; A basic electric circuit. The voltage source V on the left drives a current I around the circuit, delivering electrical energy into the resistor R. From the resistor, the current returns to the source, completing the circuit. An electric circuit is an interconnection of electric components such that electric charge is made to flow along a closed path (a circuit), usually to perform some useful task. The components in an electric circuit can take many forms, which can include elements such as resistors, capacitors, switches, transformers and electronics. Electronic circuits contain active components, usually semiconductors, and typically exhibit non-linear behavior, requiring complex analysis. The simplest electric components are those that are termed passive and linear: while they may temporarily store energy, they contain no sources of it, and exhibit linear responses to stimuli. The resistor is perhaps the simplest of passive circuit elements: as its name suggests, it resists the current through it, dissipating its energy as heat. The resistance is a consequence of the motion of charge through a conductor: in metals, for example, resistance is primarily due to collisions between electrons and ions. Ohm's law is a basic law of circuit theory, stating that the current passing through a resistance is directly proportional to the potential difference across it. The resistance of most materials is relatively constant over a range of temperatures and currents; materials under these conditions are known as 'ohmic'. The ohm, the unit of resistance, was named in honor of Georg Ohm, and is symbolized by the Greek letter Ω. 1 Ω is the resistance that will produce a potential difference of one volt in response to a current of one amp.

The capacitor is a development of the Leyden jar and is a device capable of storing charge, and thereby storing electrical energy in the resulting field. Conceptually, it consists of two conducting plates separated by a thin insulating layer; in practice, thin metal foils are coiled together, increasing the surface area per unit volume and therefore the capacitance. The unit of capacitance is the farad, named after Michael Faraday, and given the symbol F: one farad is the capacitance that develops a potential difference of one volt when it stores a charge of one coulomb. A capacitor connected to a voltage supply initially causes a current as it accumulates charge; this current will however decay in time as the capacitor fills, eventually falling to zero. A capacitor will therefore not permit a steady state current, but instead blocks it.

The inductor is a conductor, usually a coil of wire that stores energy in a magnetic field in response to the current through it. When the current changes, the magnetic field does too, inducing a voltage between the ends of the conductor. The induced voltage is

proportional to the <u>time rate of change</u> of the current. The constant of proportionality is termed the <u>inductance</u>. The unit of inductance is the <u>Henry</u>, named after <u>Joseph Henry</u>, a contemporary of Faraday. One Henry is the inductance that will induce a potential difference of one volt if the current through it changes at a rate of one ampere per second. The inductor's behavior is in some regards converse to that of the capacitor: it will freely allow an unchanging current, but opposes a rapidly changing one.

Generation and transmission

Thales' experiments with amber rods were the first studies into the production of electrical energy. While this method, now known as the <u>turboelectric effect</u>, is capable of lifting light objects and even generating sparks, it is extremely inefficient. It was not until the invention of the voltaic pile in the eighteenth century that a viable source of electricity became available. The voltaic pile, and its modern descendant, the <u>electrical battery</u>, store energy chemically and make it available on demand in the form of electrical energy. The battery is a versatile and very common power source which is ideally suited to many applications, but its energy storage is finite, and once discharged it must be disposed of or recharged. For large electrical demands electrical energy must be generated and transmitted continuously over conductive transmission lines.

Electrical power is usually generated by electro-mechanical <u>generators</u> driven by <u>steam</u> produced from <u>fossil fuel</u> combustion, or the heat released from nuclear reactions; or from other sources such as <u>kinetic energy</u> extracted from wind or flowing water. The modern <u>steam turbine</u> invented by <u>Sir Charles Parsons</u> in 1884 today generates about 80 percent of the <u>electric power</u> in the world using a variety of heat sources. Such generators bear no resemblance to Faraday's homopolar disc generator of 1831, but they still rely on his electromagnetic principle that a conductor linking a changing magnetic field induces a potential difference across its ends. The invention in the late nineteenth century of the <u>transformer</u> meant that electrical power could be transmitted more efficiently at a higher voltage but lower current. Efficient <u>electrical transmission</u> meant in turn that electricity could be generated at centralized <u>power stations</u>, where it benefited from <u>economies of scale</u>, and then be dispatched relatively long distances to where it was needed.

Since electrical energy cannot easily be stored in quantities large enough to meet demands on a national scale, at all times exactly as much must be produced as is required. This requires <u>electricity utilities</u> to make careful predictions of their electrical loads, and maintain constant co-ordination with their power stations. A certain amount of generation must always be held in <u>reserve</u> to cushion an electrical grid against inevitable disturbances and losses.

Demand for electricity grows with great rapidity as a nation modernizes and its economy develops. The United States showed a 12% increase in demand during each year of the first three decades of the twentieth century, a rate of growth that is now being experienced by emerging economies such as those of India or China. Historically, the growth rate for electricity demand has outstripped that for other forms of energy.

Environmental concerns with electricity generation have led to an increased focus on generation from renewable sources, in particular from wind and hydropower. While debate can be expected to continue over the environmental impact of different means of electricity production, its final form is relatively clean.

Power

Power engineering deals with the generation, transmission and distribution of electricity as well as the design of a range of related devices. These include transformers, electric generators, electric motors, high voltage engineering and power electronics. In many regions of the world, governments maintain an electrical network called a power grid that connects a variety of generators together with users of their energy. Users purchase electrical energy from the grid, avoiding the costly exercise of having to generate their own. Power engineers may work on the design and maintenance of the power grid as well as the power systems that connect to it. Such systems are called on-grid power systems and may supply the grid with additional power, draw power from the grid or do both. Power engineers may also work on systems that do not connect to the grid, called off-grid power systems, which in some cases are preferable to on-grid systems. The future includes Satellite controlled power systems, with feedback in real time to prevent power surges and prevent blackouts.

Electronics

Electronic engineering involves the design and testing of electronic circuits that use the properties of components such as resistors, capacitors, inductors, diodes and transistors to achieve a particular functionality. The tuned circuit, which allows the user of a radio to filter out all but a single station, is just one example of such a circuit. Another example (of a pneumatic signal conditioner) is shown in the adjacent photograph.

Microelectronics

Microprocessor

Microelectronics engineering deals with the design and micro fabrication of very small electronic circuit components for use in an integrated circuit or sometimes for use on their own as a general electronic component. The most common microelectronic components are semiconductor transistors, although all main electronic components (resistors, capacitors, inductors) can be created at a microscopic level. Nan electronics is the further scaling of devices down to nanometer levels.

Microelectronic components are created by chemically fabricating wafers of semiconductors such as silicon (at higher frequencies, compound semiconductors like gallium arsenide and indium phosphide) to obtain the desired transport of electronic charge and control of current. The field of microelectronics involves a significant amount

of chemistry and material science and requires the electronic engineer working in the field to have a very good working knowledge of the effects of quantum mechanics.

Signal processing deals with the analysis and manipulation of signals. Signals can be either analog, in which case the signal varies continuously according to the information, or digital, in which case the signal varies according to a series of discrete values representing the information. For analog signals, signal processing may involve the amplification and filtering of audio signals for audio equipment or the modulation and demodulation of signals for telecommunications. For digital signals, signal processing may involve the compression, error detection and error correction of digitally sampled signals.

Signal Processing

Signal Processing is a very mathematically oriented and intensive area forming the core of digital signal processing and it is rapidly expanding with new applications in every field of electrical engineering such as communications, control, radar, TV/Audio/Video engineering, power electronics and bio-medical engineering as many already existing analog systems are replaced with their digital counterparts. Analog signal processing is still important in the design of many control systems.

DSP processor ICs are found in every type of modern electronic systems and products including, SDTV | HDTV sets, radios and mobile communication devices, Hi-Fi audio equipments, Dolby noise reduction algorithms, GSM mobile phones, mp3 multimedia players, camcorders and digital cameras, automobile control systems, noise cancelling headphones, digital spectrum analyzers, intelligent missile guidance, radar, GPS based cruise control systems and all kinds of image processing, video processing, audio processing and speech processing systems.

Instrumentation engineering deals with the design of devices to measure physical quantities such as pressure, flow and temperature. The design of such instrumentation requires a good understanding of physics that often extends beyond electromagnetic theory. For example, flight instruments measure variables such as wind speed and altitude to enable pilots the control of aircraft analytically. Similarly, thermocouples use the Peltier-Seebeck effect to measure the temperature difference between two points.

Often instrumentation is not used by itself, but instead as the sensors of larger electrical systems. For example, a thermocouple might be used to help ensure a furnace's temperature remains constant. For this reason, instrumentation engineering is often viewed as the counterpart of control engineering.

Computer engineering deals with the design of computers and computer systems. This may involve the design of new hardware, the design of PDAs and supercomputers or the use of computers to control an industrial plant. Computer engineers may also work on a system's software. However, the design of complex software systems is often the domain of software engineering, which is usually considered a separate discipline. Desktop

computers represent a tiny fraction of the devices a computer engineer might work on, as computer-like architectures are now found in a range of devices including video game consoles and DVD players.

Electronic design automation

Electronic design automation (EDA or ECAD) is a category of software tools for designing electronic systems such as printed circuit boards and integrated circuits. The tools work together in a design flow that chip designers use to design and analyze entire semiconductor chips. Current digital flows are extremely modular (see Integrated circuit design, Design closure, and Design flow (EDA)). The front ends produce standardized design descriptions that compile into invocations of "cells,", without regard to the cell technology. Cells implement logic or other electronic functions using a particular integrated circuit technology. Fabricators generally provide libraries of components for their production processes, with simulation models that fit standard simulation tools. Analog EDA tools are far less modular, since many more functions are required, they interact more strongly, and the components are (in general) less ideal.

High-level synthesis (HLS), sometimes referred to as C synthesis, electronic system level (ESL) synthesis, algorithmic synthesis, or behavioral synthesis, is an automated design process that interprets an algorithmic description of a desired behavior and creates hardware that implements that behavior.[1] The starting point of a high-level synthesis flow is ANSI C/C++/SystemC code. The code is analyzed, architecturally constrained, and scheduled to create a register transfer level hardware design language (HDL), which is then in turn commonly synthesized to the gate level by the use of a logic synthesis tool. The goal of HLS is to let hardware designers efficiently build and verify hardware, by giving them better control over optimization of their design architecture, and through the nature of allowing the designer to describe the design at a higher level of tools while the tool does the RTL implementation. Verification of the RTL is an important part of the process. While logic synthesis uses an RTL description of the design, high-level synthesis works at a higher level of abstraction, starting with an algorithmic description in a high-level language such as SystemC and Ansi C/C++. The designer typically develops the module functionality and the interconnect protocol. The high-level synthesis tools handle the micro-architecture and transform untimed or partially timed functional code into fully timed RTL implementations, automatically creating cycle-by-cycle detail for hardware implementation. The (RTL) implementations are then used directly in a conventional logic synthesis flow to create a gate-level implementation. Source Input; The most common source inputs for high level synthesis are based on standards languages such as ANSI C/C++ and SystemC. High level synthesis typically also includes a bit-accurate executable specification as input, since to derive an efficient hardware implementation, additional information is needed on what is an acceptable Mean-Square Error or Bit-Error Rate etc. For example, if the designer starts with a FIR filter written using the "double" floating type, before he or she can derive an efficient hardware implementation, they need to perform

numerical refinement to arrive at a fixed-point implementation. The refinement requires additional information on the level of quantization noise that can be tolerated, the valid input ranges etc. This bit-accurate specification makes the high level synthesis source specification functionally complete. Process stages

The high-level synthesis process consists of a number of activities. Various high-level synthesis tools perform these activities in different orders using different algorithms. Some high-level synthesis tools combine some of these activities or perform them iteratively to converge on the desired solution.

- Lexical processing
- Algorithm optimization
- Control/Dataflow analysis
- Library processing
- Resource allocation
- Scheduling
- Functional unit binding
- Register binding
- Output processing
- Input Rebundling

Functionality

Architectural constraints

Synthesis constraints for the architecture can automatically be applied based on the design analysis. These constraints can be broken into

- Hierarchy
- Interface
- Memory
- Loop
- Low-level timing constraints
- iteration

Interface synthesis

Interface Synthesis refers to the ability to accept pure C/C++ description as its input, then use automated interface synthesis technology to control the timing and communications protocol on the design interface. This enables interface analysis and exploration of a full range of hardware interface options such as streaming, single- or dual-port RAM plus various handshaking mechanisms. With interface synthesis the designer does not embed interface protocols in the source description. Examples might be: direct connection, one line, 2 line handshake, FIFO.

Electronic system level (ESL) design and verification is an emerging electronic design methodology that focuses on the higher abstraction level concerns first and foremost. The term Electronic System Level or ESL Design was first defined by Gartner Dataquest, a EDA-industry-analysis firm, on February 1, 2001. It is defined in the ESL Design and Verification book as: "the utilization of appropriate abstractions in order to increase comprehension about a system, and to enhance the probability of a successful implementation of functionality in a cost-effective manner."

The basic premise is to model the behavior of the entire system using a high-level language such as C, C++, LabVIEW, or MATLAB or using graphical "model-based" design tools like SystemVue or Simulink. Newer languages are emerging that enable the creation of a model at a higher level of abstraction including general purpose system design languages like SysML as well as those that are specific to embedded system design like SMDL and SSDL supported by emerging system design automation products like Teraptor.[3] Rapid and correct-by-construction implementation of the system can be automated using EDA tools such as high-level synthesis and embedded software tools, although much of it is performed manually today. ESL can also be accomplished through the use of SystemC as an abstract modeling language.

Electronic System Level is now an established approach at most of the world's leading System-on-a-chip (SoC) design companies, and is being used increasingly in system design. From its genesis as an algorithm modeling methodology with 'no links to implementation', ESL is evolving into a set of complementary methodologies that enable embedded system design, verification, and debugging through to the hardware and software implementation of custom SoC, system-on-FPGA, system-on-board, and entire multi-board systems.

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Hardware design can be created at a variety of levels of abstraction. The commonly used levels of abstraction are gate level, register transfer level (RTL), and algorithmic level.

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High-level verification (HLV), or electronic system level verification, is the task to verify ESL designs at high abstraction level. i.e. it is the task to verify a model that represents hardware above register transfer level abstract level. For HLS High-level synthesis (or c synthesis), HLV is to HLS as functional verification is to logic synthesis.

Electronic digital hardware design has evolved from low level abstraction at gate level to register transfer level (RTL), the abstraction level above RTL is commonly called high-level, ESL, or behavioral/algorithmic level.

In High-level synthesis, behavioral/algorithmic designs in ANSI C/C++/SystemC code is synthesized to RTL, which is then synthesized into gate level through logic synthesis. Functional verification is the task to make sure a design at RTL or gate level conforms to a specification. As logic synthesis matures, most functional verification is done at the higher abstraction, i.e. at RTL level, the correctness of logic synthesis tool in the translating process from RTL description to gate netlist is a less concern today.

High-level synthesis is still an emerging technology, so High-level verification today has two important areas under development:
1) to validate HLS is correct in the translation process, i.e. to validate the design before and after HLS are equivalent, typically through formal methods
2) to verify a design in ANSI C/C++/SystemC code is conforming to a specification, typically through simulation.

Integrated circuit design

Layout view of a simple CMOS Operational Amplifier (inputs are to the left and the compensation capacitor is to the right). The metal layer is coloured blue, green and brown are N- and P-doped Si, the polysilicon is red and vias are crosses.

Integrated circuit design, or IC design, is a subset of electrical engineering and computer engineering, encompassing the particular logic and circuit design techniques required to

design integrated circuits, or ICs. ICs consist of miniaturized electronic components built into an electrical network on a monolithic semiconductor substrate by photolithography. IC design can be divided into the broad categories of digital and analog IC design. Digital IC design is to produce components such as microprocessors, FPGAs, memories (RAM, ROM, and flash) and digital ASICs. Digital design focuses on logical correctness, maximizing circuit density, and placing circuits so that clock and timing signals are routed efficiently. Analog IC design also has specializations in power IC design and RF IC design. Analog IC design is used in the design of op-amps, linear regulators, phase locked loops, oscillators and active filters. Analog design is more concerned with the physics of the semiconductor devices such as gain, matching, power dissipation, and resistance. Fidelity of analog signal amplification and filtering is usually critical and as a result, analog ICs use larger area active devices than digital designs and are usually less dense in circuitry. Modern ICs are enormously complicated. A large chip, as of 2009 has close to 1 billion transistors. The rules for what can and cannot be manufactured are also extremely complex. An IC process as of 2006 may well have more than 600 rules. Furthermore, since the manufacturing process itself is not completely predictable, designers must account for its statistical nature. The complexity of modern IC design, as well as market pressure to produce designs rapidly, has led to the extensive use of automated design tools in the IC design process. In short, the design of an IC using EDA software is the design, test, and verification of the instructions that the IC is to carry out. Fundamentals; Integrated circuit design involves the creation of electronic components, such as transistors, resistors, capacitors and the metallic interconnect of these components onto a piece of semiconductor, typically silicon. A method to isolate the individual components formed in the substrate is necessary since the substrate silicon is conductive and often forms an active region of the individual components. The two common methods are p-n junction isolation and dielectric isolation. Attention must be given to power dissipation of transistors and interconnect resistances and current density of the interconnect, contacts and vias since ICs contain very tiny devices compared to discrete components, where such concerns are less of an issue. Electromigration in metallic interconnect and ESD damage to the tiny components are also of concern. Finally, the physical layout of certain circuit sub blocks is typically critical, in order to achieve the desired speed of operation, to segregate noisy portions of an IC from quiet portions, to balance the effects of heat generation across the IC, or to facilitate the placement of connections to circuitry outside the IC. Digital design; Roughly speaking, digital IC design can be divided into three parts.

- Electronic system-level design: This step creates the user functional specification. The user may use a variety of languages and tools to create this description. Examples include a C/C++ model, SystemC, SystemVerilog Transaction Level Models, Simulink and MATLAB.
- RTL design: This step converts the user specification (what the user wants the chip to do) into a register transfer level (RTL) description. The RTL describes the exact behavior of the digital circuits on the chip, as well as the interconnections to inputs and outputs.

- Physical design: This step takes the RTL, and a library of available logic gates, and creates a chip design. This involves figuring out which gates to use, defining places for them, and wiring them together.

Note that the second step, RTL design, is responsible for the chip doing the right thing. The third step, physical design, does not affect the functionality at all (if done correctly) but determines how fast the chip operates and how much it costs. RTL design; This is the hardest part, and the domain of <u>functional verification</u>. The spec may have some terse description, such as encodes in the <u>MP3</u> format or implements <u>IEEE floating-point arithmetic</u>. Each of these innocent looking statements expands to hundreds of pages of text, and thousands of lines of computer code. It is extremely difficult to verify that the RTL will do the right thing in all the possible cases that the user may throw at it. Many techniques are used, none of them perfect but all of them useful – extensive <u>logic simulation</u>, <u>formal methods</u>, <u>hardware emulation</u>, <u>lint</u>-like code checking, and so on. A tiny error here can make the whole chip useless, or worse. The famous <u>Pentium FDIV bug</u> caused the results of a division to be wrong by at most 61 parts per million, in cases that occurred very infrequently. No one even noticed it until the chip had been in production for months.

Analog design

Before the advent of the microprocessor and software based design tools, analog ICs were designed using hand calculations. These ICs were basic circuits, <u>op-amps</u> are one example, usually involving no more than ten transistors and few connections. An iterative trial-and-error process and "overengineering" of device size was often necessary to achieve a manufacturability IC. Reuse of proven designs allowed progressively more complicated ICs to be built upon prior knowledge. When inexpensive computer processing became available in the 1970s, computer programs were written to simulate circuit designs with greater accuracy than practical by hand calculation. The first circuit simulator for analog ICs was called <u>SPICE</u> (Simulation Program with Integrated Circuits Emphasis). Computerized circuit simulation tools enable greater IC design complexity than hand calculations can achieve, making the design of analog <u>ASICs</u> practical. The computerized circuit simulators also enable mistakes to be found early in the design cycle before a physical device is <u>fabricated</u>. Additionally, a computerized circuit simulator can implement more sophisticated device models and circuit analysis too tedious for hand calculations, permitting <u>Monte Carlo analysis</u> and process sensitivity analysis to be practical. The effects of parameters such as temperature variation, doping concentration variation and statistical process variations can be simulated easily to determine if an IC <u>design is manufacturability</u>. Overall, computerized circuit simulation enables a higher degree of confidence that the circuit will work as expected upon manufacture.

Coping with variability

A challenge most critical to analog IC design involves the variability of the individual devices built on the semiconductor chip. Unlike board-level circuit design which permits the designer to select devices that have each been tested and <u>binned</u> according to value,

the device values on an IC can vary widely which are uncontrollable by the designer. For example, some IC resistors can vary ±20% and β of an integrated BJT can vary from 20 to 100. To add to the design challenge, device properties often vary between each processed semiconductor wafer. Device properties can even vary significantly across each individual IC due to doping gradients. The underlying cause of this variability is that many semiconductor devices are highly sensitive to uncontrollable random variances in the process. Slight changes to the amount of diffusion time, uneven doping levels, etc. can have large effects on device properties.

Some design techniques used to reduce the effects of the device variation are:

- Using the ratios of resistors, which do match closely, rather than absolute resistor value.
- Using devices with matched geometrical shapes so they have matched variations.
- Making devices large so that statistical variations becomes an insignificant fraction of the overall device property.
- Segmenting large devices, such as resistors, into parts and interweaving them to cancel variations.
- Using common centroid device layout to cancel variations in devices which must match closely (such as the transistor differential pair of an op amp).

Control theory

There are two major divisions in control theory, namely, classical and modern, which have direct implications over the control engineering applications. The scope of classical control theory is limited to single-input and single-output (SISO) system design. The system analysis is carried out in time domain using differential equations, in complex-s domain with Laplace transform or in frequency domain by transforming from the complex-s domain. All systems are assumed to be second order and single variable, and higher-order system responses and multivariable effects are ignored. A controller designed using classical theory usually requires on-site tuning due to design approximations. Yet, due to easier physical implementation of classical controller designs as compared to systems designed using modern control theory, these controllers are preferred in most industrial applications. The most common controllers designed using classical control theory are PID controllers.

In contrast, modern control theory is carried out in the state space, and can deal with multi-input and multi-output (MIMO) systems. This overcomes the limitations of classical control theory in more sophisticated design problems, such as fighter aircraft control. In modern design, a system is represented as a set of first order differential equations defined using state variables. Nonlinear, multivariable, adaptive and robust control theories come under this division. Being fairly new, modern control theory has

many areas yet to be explored. Scholars like <u>Rudolf E. Kalman</u> and <u>Aleksandr Lyapunov</u> are well-known among the people who have shaped modern control theory.

Control systems

Control engineering is the engineering <u>discipline</u> that focuses on the <u>modeling</u> of a diverse range of <u>dynamic systems</u> (e.g. <u>mechanical</u> <u>systems</u>) and the design of <u>controllers</u> that will cause these systems to behave in the desired manner. Although such controllers need not be electrical many are and hence control engineering is often viewed as a subfield of electrical engineering. However, the falling price of microprocessors is making the actual implementation of a control system essentially trivial[<u>citation needed</u>]. As a result, focus is shifting back to the mechanical engineering discipline, as intimate knowledge of the physical system being controlled is often desired.

<u>Electrical circuits</u>, <u>digital signal processors</u> and <u>microcontrollers</u> can all be used to implement <u>Control systems</u>. Control engineering has a wide range of applications from the flight and propulsion systems of <u>commercial airliners</u> to the <u>cruise control</u> present in many modern <u>automobiles</u>.

In most of the cases, control engineers utilize <u>feedback</u> when designing <u>control systems</u>. This is often accomplished using a <u>PID controller</u> system. For example, in an <u>automobile</u> with <u>cruise control</u> the vehicle's <u>speed</u> is continuously monitored and fed back to the system, which adjusts the <u>motor's</u> <u>torque</u> accordingly. Where there is regular feedback, <u>control theory</u> can be used to determine how the system responds to such feedback. In practically all such systems <u>stability</u> is important and control theory can help ensure stability is achieved.

Although feedback is an important aspect of control engineering, control engineers may also work on the control of systems without feedback. This is known as <u>open loop control</u>. A classic example of <u>open loop control</u> is a <u>washing machine</u> that runs through a pre-determined cycle without the use of <u>sensors</u>.

Originally, control engineering was all about continuous systems. Development of computer control tools posed a requirement of discrete control system engineering because the communications between the computer-based digital controller and the physical system are governed by a <u>computer clock</u>. The equivalent to <u>Laplace transform</u> in the discrete domain is the <u>z-transform</u>. Today many of the control systems are computer controlled and they consist of both digital and analog components.

Therefore, at the design stage either digital components are mapped into the continuous domain and the design is carried out in the continuous domain, or analog components are mapped in to discrete domain and design is carried out there. The first of these two methods is more commonly encountered in practice because many industrial systems have many continuous systems components, including mechanical, fluid, biological and analog electrical components, with a few digital controllers.

Similarly, the design technique has progressed from paper-and-ruler based manual design to computer-aided design, and now to computer-automated design (CAutoD), which has been made possible by evolutionary computation. CAutoD can be applied not just to tuning a predefined control scheme, but also to controller structure optimisation, system identification and invention of novel control systems, based purely upon a performance requirement, independent of any specific control scheme.

Adaptive Control is the control method used by a controller which must adapt to a controlled system with parameters which vary, or are initially uncertain. For example, as an aircraft flies, its mass will slowly decrease as a result of fuel consumption; a control law is needed that adapts itself to such changing conditions. Adaptive control is different from robust control in that it does not need a priori information about the bounds on these uncertain or time-varying parameters; robust control guarantees that if the changes are within given bounds the control law need not be changed, while adaptive control is concerned with control law changes themselves.

The foundation of adaptive control is parameter estimation. Common methods of estimation include recursive least squares and gradient descent. Both of these methods provide update laws which are used to modify estimates in real time (i.e., as the system operates). Lyapunov stability is used to derive these update laws and show convergence criterion (typically persistent excitation). Projection (mathematics) and normalization are commonly used to improve the robustness of estimation algorithms.

Classification of adaptive control techniques

In general one should distinguish between:

1. Feed forward Adaptive Control
2. Feedback Adaptive Control

as well as between

1. Direct Methods and
2. Indirect Methods

Direct methods are ones wherein the estimated parameters are those directly used in the adaptive controller. In contrast, indirect methods are those in which the estimated parameters are used to calculate required controller parameters

There are several broad categories of feedback adaptive control (classification can vary):

- Dual Adaptive Controllers [based on Dual control theory]
    - Optimal Dual Controllers [difficult to design]
    - Suboptimal Dual Controllers
- Nondual Adaptive Controllers
    - Adaptive Pole Placement

- o Extremism Seeking Controllers
- o Iterative learning control
- o Gain scheduling
- o Model Reference Adaptive Controllers (MRACs) [incorporate a reference model defining desired closed loop performance]

Gradient Optimization MRACs [use local rule for adjusting params when performance differs from reference. Ex.: "MIT rule".]

- § Stability Optimized MRACs
- o Model Identification Adaptive Controllers (MIACs) [perform System identification while the system is running]
  - § Cautious Adaptive Controllers [use current SI to modify control law, allowing for SI uncertainty]
  - § Certainty Equivalent Adaptive Controllers [take current SI to be the true system, assume no uncertainty]
    - § Nonparametric Adaptive Controllers
    - § Parametric Adaptive Controllers
      - § Explicit Parameter Adaptive Controllers
      - § Implicit Parameter Adaptive Controllers

Some special topics in adaptive control can be introduced as well:

1. Adaptive Control Based on Discrete-Time Process Identification
2. Adaptive Control Based on the Model Reference Technique
3. Adaptive Control based on Continuous-Time Process Models
4. Adaptive Control of Multivariable Processes
5. Adaptive Control of Nonlinear Processes

Applications

When designing adaptive control systems, special consideration is necessary of convergence and robustness issues. Lyapunov stability is typically used to derive control adaptation laws and show convergence.

Typical applications of adaptive control are (in general):

- Self-tuning of subsequently fixed linear controllers during the implementation phase for one operating point;
- Self-tuning of subsequently fixed robust controllers during the implementation phase for whole range of operating points;
- Self-tuning of fixed controllers on request if the process behaviour changes due to ageing, drift, wear etc.;
- Adaptive control of linear controllers for nonlinear or time-varying processes;
- Adaptive control or self-tuning control of nonlinear controllers for nonlinear processes;

- Adaptive control or self-tuning control of multivariable controllers for multivariable processes (MIMO systems);

Usually these methods adapt the controllers to both the process statics and dynamics. In special cases the adaptation can be limited to the static behavior alone, leading to adaptive control based on characteristic curves for the steady-states or to extremum value control, optimizing the steady state. Hence, there are several ways to apply adaptive control algorithms.

In control theory Advanced process control (APC) is a broad term composed of different kinds of process control tools, often used for solving multivariable control problems or discrete control problem. Advanced control describes a practice which draws elements from many disciplines ranging from control engineering, signal processing, statistics, decision theory and artificial intelligence.

APC applications are often used for solving multivariable control or discrete control problems.

Normally an APC system is connected to a distributed control system (DCS). The APC application will calculate moves that are sent to regulatory controllers. Historically the interfaces between DCS and APC systems were dedicated software interfaces. Nowadays the communication protocol between these system is managed via the industry standard OLE for process control (OPC) protocol.

Advanced process control: Topics

APC industries

- APC can be found in the (petro)chemical industries where it makes it possible to control multivariable control problems. Since these controllers contain the dynamic relationships between variables it can predict in the future how variables will behave. Based on these predictions, actions can be taken now to maintain variables within their limits. APC is used when the models can be estimated and do not vary too much.

- In the complex semiconductor industry where several hundred steps with multiple re-entrant possibilities occurs, APC plays an important role for control the overall production.

APC is more and more used in other industries. In the mining industry for example, successful applications of APC (often combine to Fuzzy Logic) have been successfully implemented. In the mining industry, the models change and APC implementation is more complex.

APC Engineers

Those responsible for the design, implementation and maintenance of APC applications are often referred to as APC Engineers or Control Application Engineers. Usually their education is dependent upon the field of specialization. For example, in the chemical industry the vast majority of APC Engineers have a chemical engineering background and typically hold a graduate degree. They combine deep understanding of advanced control techniques with expert process or product knowledge to provide solutions to the most difficult control problems. Because APC engineers are highly specialized many companies elect to contract engineering firms for this type of work. However, some companies view APC as a competitive advantage and maintain a staff of APC engineers who often provide services at more than one geographic location.

Terminology

Manipulated Variables (MVs) are variables where advanced controllers send setpoints to. Controlled variables (CVs) are variables that normally need to be controlled between limits. Disturbance variables (DVs) or Feed Forward variables (FF) are only used as an input to the controller, they cannot be influenced, but when measured contribute to the predictability of the CV.

Building automation describes the advanced functionality provided by the control system of a building. A building automation system (BAS) is an example of a distributed control system. The control system is a computerized, intelligent network of electronic devices designed to monitor and control the mechanical electronics, and lighting systems in a building.

BAS core functionality keeps the building climate within a specified range, provides lighting based on an occupancy schedule, and monitors system performance and device failures and provides email and/or text notifications to building engineering/maintenance staff. The BAS functionality reduces building energy and maintenance costs when compared to a non-controlled building. A building controlled by a BAS is often referred to as an intelligent building system or a Smart home.

Topology

Most building automation networks consist of a primary and secondary bus which connect high-level controllers (generally specialized for building automation, but may be generic programmable logic controllers) with lower-level controllers, input/output devices and a user interface (also known as a human interface device).

The primary and secondary bus can be BACnet, optical fiber, ethernet, ARCNET, RS-232, RS-485 or a wireless network.

Most controllers are underlined proprietary. Each company has its own controllers for specific applications. Some are designed with limited controls: for example, a simple Packaged Roof Top Unit. Others are designed to be flexible. Most have proprietary software that will work with ASHRAE's open protocol BACnet or the open protocol LonTalk.

Some newer building automation and lighting control solutions use wireless mesh open standards (such as ZigBee). These systems can provide interoperability, allowing users to mix-and-match devices from different manufacturers, and to provide integration with other compatible building control systems.

Inputs and outputs are either analog or digital (some companies say binary).

Analog inputs are used to read a variable measurement. Examples are temperature, humidity and pressure sensor which could be thermistor, 4-20 mA, 0-10 volt or platinum resistance thermometer (resistance temperature detector), or wireless sensors.

A digital input indicates if a device is turned on or not. Some examples of a digital input would be a 24VDC/AC signal, an air flow switch, or a volta-free relay contact (Dry Contact).

Analog outputs control the speed or position of a device, such as a variable frequency drive, a I-P (current to pneumatics) transducer, or a valve or damper actuator. An example is a hot water valve opening up 25% to maintain a setpoint.

Digital outputs are used to open and close relays and switches. An example would be to turn on the parking lot lights when a photocell indicate it is dark outside.

Infrastructure

Controller

Controllers are essentially small, purpose-built computers with input and output capabilities. These controllers come in a range of sizes and capabilities to control devices commonly found in buildings, and to control sub-networks of controllers.

Inputs allow a controller to read temperatures, humidity, pressure, current flow, air flow, and other essential factors. The outputs allow the controller to send command and control signals to slave devices, and to other parts of the system. Inputs and outputs can be either digital or analog. Digital outputs are also sometimes called discrete depending on manufacturer.

Controllers used for building automation can be grouped in 3 categories. Programmable Logic Controllers (PLCs), System/Network controllers, and Terminal Unit controllers. However an additional device can also exist in order to integrate 3rd party systems (i.e. a stand-alone AC system) into a central Building automation system).

PLC's provide the most responsiveness and processing power, but at a unit cost typically 2 to 3 times that of a System/Network controller intended for BAS applications. Terminal Unit controllers are usually the least expensive and least powerful.

PLC's may be used to automate high-end applications such as clean rooms or hospitals where the cost of the controllers is less of a concern.

In office buildings, supermarkets, malls, and other common automated buildings the systems will use System/Network controllers rather than PLC's. Most System controllers provide general purpose feedback loops, as well as digital circuits, but lack the millisecond response time that PLC's provide.

System/Network controllers may be applied to control one or more mechanical systems such as an Air Handler Unit (AHU), boiler, chiller, etc., or they may supervise a sub-network of controllers. In the diagram above, System/Network controllers are often used in place of PLCs.

Terminal Unit controllers usually are suited for control of lighting and/or simpler devices such as a package rooftop unit, heat pump, VAV box, or fan coil, etc. The installer typically selects 1 of the available pre-programmed personalities best suited to the device to be controlled, and does not have to create new control logic.

Coefficient diagram method

Coefficient diagram method (CDM), developed and introduced by Prof. Shunji Manabe in 1991. CDM is an algebraic approach applied to a polynomial loop in the parameter space, where a special diagram called a "coefficient diagram" is used as the vehicle to carry the necessary information, and as the criteria of good design. The performance of the closed loop system is monitored by the coefficient diagram.

The most important properties of the method are: the adaptation of the polynomial representation for both the plant and the controller, the use of the two-degree of freedom (2DOF) control system structure, the nonexistence (or very small) of the overshoot in the step response of the closed loop system, the determination of the settling time at the start and to continue the design accordingly, the good robustness for the control system with respect to the plant parameter changes, the sufficient gain and phase margins for the controller. The most considerable advantages of CDM can be listed as follows:

1. The design procedure is easily understandable, systematic and useful. Therefore, the coefficients of the CDM controller polynomials can be determined more easily than those of the PID or other types of controller. This creates the possibility of an easy realisation for a new designer to control any kind of system.

2. There are explicit relations between the performance parameters specified before the design and the coefficients of the controller polynomials as described in. For this reason, the designer can easily realize many control systems having different performance properties for a given control problem in a wide range of freedom.

3. The development of different tuning methods is required for time delay processes of different properties in PID control. But it is sufficient to use the single design procedure in the CDM technique. This is an outstanding advantage.

4. It is particularly hard to design robust controllers realizing the desired performance properties for unstable, integrating and oscillatory processes having poles near the imaginary axis. It has been reported that successful designs can be achieved even in these cases by using CDM

5. It is theoretically proven that CDM design is equivalent to LQ design with proper state augmentation. Thus, CDM can be considered an ''improved LQG'', because the order of the controller is smaller and weight selection rules are also given

It is usually required that the controller for a given plant should be designed under some practical limitations. The controller is desired to be of minimum degree, minimum phase (if possible) and stable. It must have enough bandwidth and power rating limitations. If the controller is designed without considering these limitations, the robustness property will be very poor, even though the stability and time response requirements are met. CDM controllers designed while considering all these problems is of the lowest degree, has a convenient bandwidth and results with a unit step time response without an overshoot. These properties guarantee the robustness, the sufficient damping of the disturbance effects and the low economic property

Although the main principles of CDM have been known since the 1950s, the first systematic method was proposed by Shunji Manabe. He developed a new method that easily builds a target characteristic polynomial to meet the desired time response. CDM is an algebraic approach combining classical and modern control theories and uses polynomial representation in the mathematical expression. The advantages of the classical and modern control techniques are integrated with the basic principles of this method, which is derived by making use of the previous experience and knowledge of the controller design. Thus, an efficient and fertile control method has appeared as a tool with which control systems can be designed without needing much experience and without confronting many problems.

Many control systems have been designed successfully using CDM. It is very easy to design a controller under the conditions of stability, time domain performance and robustness. The close relations between these conditions and coefficients of the characteristic polynomial can be simply determined. This means that CDM is effective not only for control system design but also for controller parameters tuning.

Computer-automated design

Design Automation usually refers to electronic design automation. Extending Computer-Aided Design (CAD), automated design and Computer-Automated Design (CAutoD) [1][2][3] are more concerned with a broader range of applications, such as automotive engineering, civil engineering [4][5][6][7], composite material design, control engineering [8], dynamic system identification [9], financial systems, industrial equipment, mechatronic systems, steel construction [10], structural optimisation, and the invention of novel systems.

The concept of CAutoD perhaps first appeared in 1963, in the IBM Journal of Research and Development [1], where a computer program was written (1) to search for logic circuits having certain constraints on hardware design and (2) to evaluate these logics in terms of their discriminating ability over samples of the character set they are expected to recognize. More recently, traditional CAD simulation is seen to be transformed to CAutoD by biologically-inspired machine learning or search techniques such as evolutionary computation, including swarm intelligence algorithms.

Designs by performance improvements

To meet the ever growing demand of quality and competitiveness, iterative physical prototyping is now often replaced by 'digital prototyping' of a 'good design', which aims to meet multiple objectives such as maximized output, energy efficiency, highest speed and cost-effectiveness. The design problem concerns both finding the best design within a known range (i.e., through 'learning' or 'optimisation') and finding a new and better design beyond the existing ones (i.e., through creation and invention). This is equivalent to a search problem in an, almost certainly, multidimensional (multivariate), multi-modal space with a single (or weighted) objective or multiple objectives.

Control reconfiguration is an active approach in control theory to achieve fault-tolerant control for dynamic systems. It is used when severe faults, such as actuator or sensor outages, cause a break-up of the control loop, which must be restructured to prevent failure at the system level. In addition to loop restructuring, the controller parameters must be adjusted to accommodate changed plant dynamics. Control reconfiguration is a building block toward increasing the dependability of systems under feedback control.

Control theory is an interdisciplinary branch of engineering and mathematics that deals with the behavior of dynamical systems. The external input of a system is called the reference. When one or more output variables of a system need to follow a certain reference over time, a controller manipulates the inputs to a system to obtain the desired effect on the output of the system.

The usual objective of a control theory is to calculate solutions for the proper corrective action from the controller that result in system stability, that is, the system will hold the set point and not oscillate around it.

The inputs and outputs of a continuous control system are generally related by nonlinear differential equations. A transfer function can sometimes be obtained by

1. Finding a solution of the nonlinear differential equations,
2. Linearizing the nonlinear differential equations at the resulting solution (i.e. trim point),
3. Finding the Laplace Transform of the resulting linear differential equations, and
4. Solving for the outputs in terms of the inputs in the Laplace domain.

The transfer function is also known as the system function or network function. The transfer function is a mathematical representation, in terms of spatial or temporal frequency, of the relation between the input and output of a linear time-invariant solution of the nonlinear differential equations describing the system.

Classical control theory

To avoid the problems of the open-loop controller, control theory introduces feedback. A closed-loop controller uses feedback to control states or outputs of a dynamical system. Its name comes from the information path in the system: process inputs (e.g., voltage applied to an electric motor) have an effect on the process outputs (e.g., speed or torque of the motor), which is measured with sensors and processed by the controller; the result (the control signal) is used as input to the process, closing the loop.

Closed-loop controllers have the following advantages over open-loop controllers:

- disturbance rejection (such as unmeasured friction in a motor)
- guaranteed performance even with model uncertainties, when the model structure does not match perfectly the real process and the model parameters are not exact
- unstable processes can be stabilized
- reduced sensitivity to parameter variations
- improved reference tracking performance

In some systems, closed-loop and open-loop control are used simultaneously. In such systems, the open-loop control is termed feedforward and serves to further improve reference tracking performance.

A common closed-loop controller architecture is the PID controller.

Modern control theory

In contrast to the frequency domain analysis of the classical control theory, modern control theory utilizes the time-domain state space representation, a mathematical model of a physical system as a set of input, output and state variables related by first-order differential equations. To abstract from the number of inputs, outputs and states, the variables are expressed as vectors and the differential and algebraic equations are written in matrix form (the latter only being possible when the dynamical system is linear). The

state space representation (also known as the "time-domain approach") provides a convenient and compact way to model and analyze systems with multiple inputs and outputs. With inputs and outputs, we would otherwise have to write down Laplace transforms to encode all the information about a system. Unlike the frequency domain approach, the use of the state space representation is not limited to systems with linear components and zero initial conditions. "State space" refers to the space whose axes are the state variables. The state of the system can be represented as a vector within that space

Topics in control theory

Stability

The stability of a general <u>dynamical system</u> with no input can be described with <u>Lyapunov stability</u> criteria. A <u>linear system</u> that takes an input is called <u>bounded-input bounded-output (BIBO) stable</u> if its output will stay <u>bounded</u> for any bounded input. Stability for <u>nonlinear systems</u> that take an input is <u>input-to-state stability</u> (ISS), which combines Lyapunov stability and a notion similar to BIBO stability. For simplicity, the following descriptions focus on continuous-time and discrete-time linear systems.

Mathematically, this means that for a causal linear system to be stable all of the <u>poles</u> of its <u>transfer function</u> must have negative-real values, i.e. the real part of all the poles are less than zero. Practically speaking, stability requires that the transfer function complex poles reside

- in the open left half of the <u>complex plane</u> for continuous time, when the <u>Laplace transform</u> is used to obtain the transfer function.
- inside the <u>unit circle</u> for discrete time, when the <u>Z-transform</u> is used.

The difference between the two cases is simply due to the traditional method of plotting continuous time versus discrete time transfer functions. The continuous Laplace transform is in <u>Cartesian coordinates</u> where the x axis is the real axis and the discrete Z-transform is in <u>circular coordinates</u> where the rho axis is the real axis.

When the appropriate conditions above are satisfied a system is said to be <u>asymptotically stable</u>: the variables of an asymptotically stable control system always decrease from their initial value and do not show permanent oscillations. Permanent oscillations occur when a pole has a real part exactly equal to zero (in the continuous time case) or a modulus equal to one (in the discrete time case). If a simply stable system response neither decays nor grows over time, and has no oscillations, it is <u>marginally stable</u>: in this case the system transfer function has non-repeated poles at complex plane origin (i.e. their real and complex component is zero in the continuous time case). Oscillations are present when poles with real part equal to zero have an imaginary part not equal to zero.

Controllability and observability

Controllability and observability are main issues in the analysis of a system before deciding the best control strategy to be applied, or whether it is even possible to control or stabilize the system. Controllability is related to the possibility of forcing the system into a particular state by using an appropriate control signal. If a state is not controllable, then no signal will ever be able to control the state. If a state is not controllable, but its dynamics are stable, then the state is termed Stabilizable. Observability instead is related to the possibility of "observing", through output measurements, the state of a system. If a state is not observable, the controller will never be able to determine the behaviour of an unobservable state and hence cannot use it to stabilize the system. However, similar to the stabilizability condition above, if a state cannot be observed it might still be detectable.

From a geometrical point of view, looking at the states of each variable of the system to be controlled, every "bad" state of these variables must be controllable and observable to ensure a good behaviour in the closed-loop system. That is, if one of the eigenvalues of the system is not both controllable and observable, this part of the dynamics will remain untouched in the closed-loop system. If such an eigenvalue is not stable, the dynamics of this eigenvalue will be present in the closed-loop system which therefore will be unstable. Unobservable poles are not present in the transfer function realization of a state-space representation, which is why sometimes the latter is preferred in dynamical systems analysis.

Solutions to problems of uncontrollable or unobservable system include adding actuators and sensors.

Control specification

Several different control strategies have been devised in the past years. These vary from extremely general ones (PID controller), to others devoted to very particular classes of systems (especially robotics or aircraft cruise control).

A control problem can have several specifications. Stability, of course, is always present: the controller must ensure that the closed-loop system is stable, regardless of the open-loop stability. A poor choice of controller can even worsen the stability of the open-loop system, which must normally be avoided. Sometimes it would be desired to obtain particular dynamics in the closed loop: i.e. that the poles have $Re[\lambda] < -\bar{\lambda}$, where $\bar{\lambda}$ is a fixed value strictly greater than zero, instead of simply asking that $Re[\lambda] < 0$.

Another typical specification is the rejection of a step disturbance; including an integrator in the open-loop chain (i.e. directly before the system under control) easily achieves this. Other classes of disturbances need different types of sub-systems to be included.

Other "classical" control theory specifications regard the time-response of the closed-loop system: these include the rise time (the time needed by the control system to reach the desired value after a perturbation), peak overshoot (the highest value reached by the

response before reaching the desired value) and others (<u>settling time</u>, quarter-decay). Frequency domain specifications are usually related to <u>robustness</u> (see after).

Modern performance assessments use some variation of integrated tracking error (IAE,ISA,CQI).

Model identification and robustness

A control system must always have some robustness property. A <u>robust controller</u> is such that its properties do not change much if applied to a system slightly different from the mathematical one used for its synthesis. This specification is important: no real physical system truly behaves like the series of differential equations used to represent it mathematically. Typically a simpler mathematical model is chosen in order to simplify calculations, otherwise the true system dynamics can be so complicated that a complete model is impossible.

System classifications

For MIMO systems, pole placement can be performed mathematically using a <u>state space representation</u> of the open-loop system and calculating a feedback matrix assigning poles in the desired positions. In complicated systems this can require computer-assisted calculation capabilities, and cannot always ensure robustness. Furthermore, all system states are not in general measured and so observers must be included and incorporated in pole placement design.

Nonlinear systems control

<u>Nonlinear control</u>

Processes in industries like <u>robotics</u> and the <u>aerospace industry</u> typically have strong nonlinear dynamics. In control theory it is sometimes possible to linearize such classes of systems and apply linear techniques, but in many cases it can be necessary to devise from scratch theories permitting control of nonlinear systems. These, e.g., <u>feedback linearization</u>, <u>backstepping</u>, <u>sliding mode control</u>, trajectory linearization control normally take advantage of results based on <u>Lyapunov's theory</u>. <u>Differential geometry</u> has been widely used as a tool for generalizing well-known linear control concepts to the non-linear case, as well as showing the subtleties that make it a more challenging problem.

Decentralized systems

<u>Decentralized/distributed control</u>

When the system is controlled by multiple controllers, the problem is one of decentralized control. Decentralization is helpful in many ways, for instance, it helps

control systems operate over a larger geographical area. The agents in decentralized control systems can interact using communication channels and coordinate their actions.

Main control strategies

Every control system must guarantee first the stability of the closed-loop behavior. For linear systems, this can be obtained by directly placing the poles. Non-linear control systems use specific theories (normally based on Aleksandr Lyapunov's Theory) to ensure stability without regard to the inner dynamics of the system. The possibility to fulfill different specifications varies from the model considered and the control strategy chosen. Here a summary list of the main control techniques is shown:

Adaptive control
> Adaptive control uses on-line identification of the process parameters, or modification of controller gains, thereby obtaining strong robustness properties. Adaptive controls were applied for the first time in the aerospace industry in the 1950s, and have found particular success in that field.

Hierarchical control
> A Hierarchical control system is a type of Control System in which a set of devices and governing software is arranged in a hierarchical tree. When the links in the tree are implemented by a computer network, then that hierarchical control system is also a form of Networked control system.

Intelligent control
> Intelligent control uses various AI computing approaches like neural networks, Bayesian probability, fuzzy logic, machine learning, evolutionary computation and genetic algorithms to control a dynamic system.

Optimal control
> Optimal control is a particular control technique in which the control signal optimizes a certain "cost index": for example, in the case of a satellite, the jet thrusts needed to bring it to desired trajectory that consume the least amount of fuel. Two optimal control design methods have been widely used in industrial applications, as it has been shown they can guarantee closed-loop stability. These are Model Predictive Control (MPC) and linear-quadratic-Gaussian control (LQG). The first can more explicitly take into account constraints on the signals in the system, which is an important feature in many industrial processes. However, the "optimal control" structure in MPC is only a means to achieve such a result, as it does not optimize a true performance index of the closed-loop control system. Together with PID controllers, MPC systems are the most widely used control technique in process control.

Robust control
> Robust control deals explicitly with uncertainty in its approach to controller design. Controllers designed using robust control methods tend to be able to cope with small differences between the true system and the nominal model used for design. The early methods of Bode and others were fairly robust; the state-space methods invented in the 1960s and 1970s were sometimes found to lack robustness. A modern example of a robust control technique is H-infinity loop-

shaping developed by <u>Duncan McFarlane</u> and <u>Keith Glover</u> of <u>Cambridge University</u>, <u>United Kingdom</u>. Robust methods aim to achieve robust performance and/or <u>stability</u> in the presence of small modeling errors.

Stochastic control

Stochastic control deals with control design with uncertainty in the model. In typical stochastic control problems, it is assumed that there exist random noise and disturbances in the model and the controller, and the control design must take into account these random deviations.

Feedback

Feedback is a process in which <u>information</u> about the past or the present influences the same <u>phenomenon</u> in the present or future. As part of a <u>chain</u> of <u>cause-and-effect</u> that forms a circuit or loop, the event is said to "feed back" into itself.

Ramaprasad (1983) defines feedback generally as "information about the gap between the actual level and the reference level of a system parameter which is used to alter the gap in some way", emphasising that the information by itself is not feedback unless translated into action.

"...'feedback' exists between two parts when each affects the other..."

Feedback is also a synonym for:

- Feedback signal - the measurement of the actual level of the parameter of interest.
- Feedback mechanism - the action or means used to subsequently modify the gap.
- Feedback loop - the complete causal path that leads from the initial detection of the gap to the subsequent modification of the gap.

Feedback is commonly divided into two types - usually termed positive and negative. The terms can be applied in two contexts:

1. the context of the gap between reference and actual values of a parameter, based on whether the gap is widening (positive) or narrowing (negative).
2. the context of the action or effect that alters the gap, based on whether it involves reward (positive) or non-reward/punishment (negative).

The two contexts may cause confusion, such as when an incentive (reward) is used to boost poor performance (narrow a gap). Referring to context 1, some authors use alternative terms, replacing 'positive/negative' with self-reinforcing/self-correctingreinforcing/balancing], discrepancy-enhancing/discrepancy-reducing or regenerative/degenerative respectively. And within context 2, some authors advocate describing the action or effect as positive/negative <u>reinforcement</u> rather than feedback. Yet even within a single context an example of feedback can be called either positive or negative, depending on how values are measured or referenced. This confusion may arise

because feedback can be used for either informational or motivational purposes, and often has both a qualitative and a quantitative component.

> "Quantitative feedback tells us how much and how many. Qualitative feedback tells us how good, bad or indifferent."

The terms "positive/negative" were first applied to feedback prior to WWII. The idea of positive feedback was already current in the 1920s with the introduction of the regenerative circuit. Friis and Jensen (1924) described regeneration in a set of electronic amplifiers as a case where the "feed-back" action is positive in contrast to negative feed-back action, which they mention only in passing. Harold Stephen Black's classic 1934 paper first details the use of negative feedback in electronic amplifiers. According to Black:

> "Positive feed-back increases the gain of the amplifier, negative feed-back reduces it."

According to Mindell (2002) confusion in the terms arose shortly after this:

> "...Friis and Jensen had made the same distinction Black used between 'positive feed-back' and 'negative feed-back', based not on the sign of the feedback itself but rather on its effect on the amplifier's gain. In contrast, Nyquist and Bode, when they built on Black's work, referred to negative feedback as that with the sign reversed. Black had trouble convincing others of the utility of his invention in part because confusion existed over basic matters of definition."

Control theory

Feedback is extensively used in control theory, using a variety of methods including state space (controls), full state feedback (also known as pole placement), and so forth. Note that in the context of control theory, "feedback" is traditionally assumed to specify "negative feedback".

PID controller

The most common general-purpose controller using a control-loop feedback mechanism is a proportional-integral-derivative (PID) controller. Heuristically, the terms of a PID controller can be interpreted as corresponding to time: the proportional term depends on the present error, the integral term on the accumulation of past errors, and the derivative term is a prediction of future error, based on current rate of change.

A proportional–integral–derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems – a PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process control inputs.

The PID controller calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D. Heuristically, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, or the power supplied to a heating element.

In the absence of knowledge of the underlying process, a PID controller has historically been considered to be the best controller. By tuning the three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the setpoint and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability.

Some applications may require using only one or two actions to provide the appropriate system control. This is achieved by setting the other parameters to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are fairly common, since derivative action is sensitive to measurement noise, whereas the absence of an integral term may prevent the system from reaching its target value due to the control action.

Industrial control system (ICS) is a general term that encompasses several types of control systems used in industrial production, including supervisory control and data acquisition (SCADA) systems, distributed control systems (DCS), and other smaller control system configurations such as skid-mounted programmable logic controllers (PLC) often found in the industrial sectors and critical infrastructures.

ICSs are typically used in industries such as electrical, water, oil, gas and data. Based on information received from remote stations, automated or operator-driven supervisory commands can be pushed to remote station control devices, which are often referred to as field devices. Field devices control local operations such as opening and closing valves and breakers, collecting data from sensor systems, and monitoring the local environment for alarm conditions.

PID controllers date to 1890s governor design. PID controllers were subsequently developed in automatic ship steering. One of the earliest examples of a PID-type controller was developed by Elmer Sperry in 1911, while the first published theoretical analysis of a PID controller was by Russian American engineer Nicolas Minorsky, in (Minorsky 1922). Minorsky was designing automatic steering systems for the US Navy, and based his analysis on observations of a helmsman, observing that the helmsman controlled the ship not only based on the current error, but also on past error and current rate of change; this was then made mathematical by Minorsky. His goal was stability, not

general control, which significantly simplified the problem. While proportional control provides stability against small disturbances, it was insufficient for dealing with a steady disturbance, notably a stiff gale (due to droop), which required adding the integral term. Finally, the derivative term was added to improve control.

In the early history of automatic process control the PID controller was implemented as a mechanical device. These mechanical controllers used a lever, spring and a mass and were often energized by compressed air. These pneumatic controllers were once the industry standard.

Electronic analog controllers can be made from a solid-state or tube amplifier, a capacitor and a resistance. Electronic analog PID control loops were often found within more complex electronic systems, for example, the head positioning of a disk drive, the power conditioning of a power supply, or even the movement-detection circuit of a modern seismometer. Nowadays, electronic controllers have largely been replaced by digital controllers implemented with microcontrollers or FPGAs.

Most modern PID controllers in industry are implemented in programmable logic controllers (PLCs) or as a panel-mounted digital controller. Software implementations have the advantages that they are relatively cheap and are flexible with respect to the implementation of the PID algorithm. PID temperature controllers are applied in industrial ovens, plastics injection machinery, hot stamping machines and packing industry.

Variable voltages may be applied by the time proportioning form of Pulse-width modulation (PWM) – a cycle time is fixed, and variation is achieved by varying the proportion of the time during this cycle that the controller outputs +1 (or −1) instead of 0. On a digital system the possible proportions are discrete – e.g., increments of .1 second within a 2 second cycle time yields 20 possible steps: percentage increments of 5% – so there is a discretization error, but for high enough time resolution this yields satisfactory performance.

Control loop basics

Control system

A familiar example of a control loop is the action taken when adjusting hot and cold faucets (valves) to maintain the water at a desired temperature. This typically involves the mixing of two process streams, the hot and cold water. The person touches the water to sense or measure its temperature. Based on this feedback they perform a control action to adjust the hot and cold water valves until the process temperature stabilizes at the desired value.

The sensed water temperature is the process variable or process value (PV). The desired temperature is called the setpoint (SP). The input to the process (the water valve position) is called the manipulated variable (MV). The difference between the temperature

measurement and the setpoint is the error (e) and quantifies whether the water is too hot or too cold and by how much.

After measuring the temperature (PV), and then calculating the error, the controller decides when to change the tap position (MV) and by how much. When the controller first turns the valve on, it may turn the hot valve only slightly if warm water is desired, or it may open the valve all the way if very hot water is desired. This is an example of a simple proportional control. In the event that hot water does not arrive quickly, the controller may try to speed-up the process by opening up the hot water valve more-and-more as time goes by. This is an example of an integral control.

Making a change that is too large when the error is small is equivalent to a high gain controller and will lead to overshoot. If the controller were to repeatedly make changes that were too large and repeatedly overshoot the target, the output would oscillate around the setpoint in either a constant, growing, or decaying sinusoid. If the oscillations increase with time then the system is unstable, whereas if they decrease the system is stable. If the oscillations remain at a constant magnitude the system is marginally stable.

In the interest of achieving a gradual convergence at the desired temperature (SP), the controller may wish to damp the anticipated future oscillations. So in order to compensate for this effect, the controller may elect to temper its adjustments. This can be thought of as a derivative control method.

If a controller starts from a stable state at zero error (PV = SP), then further changes by the controller will be in response to changes in other measured or unmeasured inputs to the process that impact on the process, and hence on the PV. Variables that impact on the process other than the MV are known as disturbances. Generally controllers are used to reject disturbances and/or implement setpoint changes. Changes in feedwater temperature constitute a disturbance to the faucet temperature control process.

In theory, a controller can be used to control any process which has a measurable output (PV), a known ideal value for that output (SP) and an input to the process (MV) that will affect the relevant PV. Controllers are used in industry to regulate temperature, pressure, flow rate, chemical composition, speed and practically every other variable for which a measurement exists.

PID controller theory

The PID control scheme is named after its three correcting terms, whose sum constitutes the manipulated variable (MV). The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining $u(t)$ as the controller output, the final form of the PID algorithm is:

$$\mathrm{u}(t) = \mathrm{MV}(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t)$$

where

K_p: Proportional gain, a tuning parameter
K_i: Integral gain, a tuning parameter
K_d: Derivative gain, a tuning parameter
e: Error $= SP - PV$
t: Time or instantaneous time (the present)

Proportional term

The proportional term produces an output value that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant Kp, called the proportional gain constant.

The proportional term is given by:

$$P_{\text{out}} = K_p\, e(t)$$

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable (see the section on loop tuning). In contrast, a small gain results in a small output response to a large input error, and a less responsive or less sensitive controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances. Tuning theory and industrial practice indicate that the proportional term should contribute the bulk of the output change.[citation needed]

Droop

Because a non-zero error is required to drive the controller, a pure proportional controller generally operates with a steady-state error, referred to as droop. Droop is proportional to the process gain and inversely proportional to proportional gain. Droop may be mitigated by adding a compensating bias term to the setpoint or output, or corrected by adding an integral term.

Integral term

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain (K_i) and added to the controller output.

The integral term is given by:

$$I_{\text{out}} = K_i \int_0^t e(\tau)\, d\tau$$

The integral term accelerates the movement of the process towards setpoint and eliminates the residual steady-state error that occurs with a pure proportional controller. However, since the integral term responds to accumulated errors from the past, it can cause the present value to <u>overshoot</u> the setpoint value (see <u>the section on loop tuning</u>).

Derivative term

The <u>derivative</u> of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain K_d. The magnitude of the contribution of the derivative term to the overall control action is termed the derivative gain, K_d.

The derivative term is given by:

$$D_{\text{out}} = K_d \frac{d}{dt} e(t)$$

The derivative term slows the rate of change of the controller output. Derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability. However, the derivative term slows the <u>transient response</u> of the controller. Also, differentiation of a signal amplifies noise and thus this term in the controller is highly sensitive to noise in the error term, and can cause a process to become unstable if the noise and the derivative gain are sufficiently large. Hence an approximation to a differentiator with a limited bandwidth is more commonly used. Such a circuit is known as a <u>phase-lead compensator</u>.

Loop tuning

Tuning a control loop is the adjustment of its control parameters (proportional band/gain, integral gain/reset, derivative gain/rate) to the optimum values for the desired control response. Stability (bounded oscillation) is a basic requirement, but beyond that, different systems have different behavior, different applications have different requirements, and requirements may conflict with one another.

PID tuning is a difficult problem, even though there are only three parameters and in principle is simple to describe, because it must satisfy complex criteria within the <u>limitations of PID control</u>. There are accordingly various methods for loop tuning, and more sophisticated techniques are the subject of patents; this section describes some traditional manual methods for loop tuning.

Designing and tuning a PID controller appears to be conceptually intuitive, but can be hard in practice, if multiple (and often conflicting) objectives such as short transient and

high stability are to be achieved. Usually, initial designs need to be adjusted repeatedly through computer simulations until the closed-loop system performs or compromises as desired.

Some processes have a degree of non-linearity and so parameters that work well at full-load conditions don't work when the process is starting up from no-load; this can be corrected by gain scheduling (using different parameters in different operating regions). PID controllers often provide acceptable control using default tunings, but performance can generally be improved by careful tuning, and performance may be unacceptable with poor tuning.

Stability

If the PID controller parameters (the gains of the proportional, integral and derivative terms) are chosen incorrectly, the controlled process input can be unstable, i.e., its output diverges, with or without oscillation, and is limited only by saturation or mechanical breakage. Instability is caused by excess gain, particularly in the presence of significant lag.

Generally, stabilization of response is required and the process must not oscillate for any combination of process conditions and setpoints, though sometimes marginal stability (bounded oscillation) is acceptable or desired.[citation needed]

Optimum behavior

The optimum behavior on a process change or setpoint change varies depending on the application.

Two basic requirements are regulation (disturbance rejection – staying at a given setpoint) and command tracking (implementing setpoint changes) – these refer to how well the controlled variable tracks the desired value. Specific criteria for command tracking include rise time and settling time. Some processes must not allow an overshoot of the process variable beyond the setpoint if, for example, this would be unsafe. Other processes must minimize the energy expended in reaching a new setpoint.

Overview of methods

There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model, then choosing P, I, and D based on the dynamic model parameters. Manual tuning methods can be relatively inefficient, particularly if the loops have response times on the order of minutes or longer.

The choice of method will depend largely on whether or not the loop can be taken "offline" for tuning, and the response time of the system. If the system can be taken offline, the best tuning method often involves subjecting the system to a step change in

input, measuring the output as a function of time, and using this response to determine the control parameters.

If the system must remain online, one tuning method is to first set K_i and K_d values to zero. Increase the K_p until the output of the loop oscillates, then the K_p should be set to approximately half of that value for a "quarter amplitude decay" type response. Then increase K_i until any offset is corrected in sufficient time for the process. However, too much K_i will cause instability. Finally, increase K_d, if required, until the loop is acceptably quick to reach its reference after a load disturbance. However, too much K_d will cause excessive response and overshoot. A fast PID loop tuning usually overshoots slightly to reach the setpoint more quickly; however, some systems cannot accept overshoot, in which case an <u>over-damped</u> closed-loop system is required, which will require a K_p setting significantly less than half that of the K_p setting causing oscillation.

Most modern industrial facilities no longer tune loops using the manual calculation methods shown above. Instead, PID tuning and loop optimization software are used to ensure consistent results. These software packages will gather the data, develop process models, and suggest optimal tuning. Some software packages can even develop tuning by gathering data from reference changes.

Mathematical PID loop tuning induces an impulse in the system, and then uses the controlled system's frequency response to design the PID loop values. In loops with response times of several minutes, mathematical loop tuning is recommended, because trial and error can take days just to find a stable set of loop values. Optimal values are harder to find. Some digital loop controllers offer a self-tuning feature in which very small setpoint changes are sent to the process, allowing the controller itself to calculate optimal tuning values.

Other formulas are available to tune the loop according to different performance criteria. Many patented formulas are now embedded within PID tuning software and hardware modules.

Advances in automated PID Loop Tuning software also deliver algorithms for tuning PID Loops in a dynamic or Non-Steady State (NSS) scenario. The software will model the dynamics of a process, through a disturbance, and calculate PID control parameters in response.

Modifications to the PID algorithm

The basic PID algorithm presents some challenges in control applications that have been addressed by minor modifications to the PID form.

Integral windup

One common problem resulting from the ideal PID implementations is <u>integral windup</u>, where a large change in setpoint occurs (say a positive change) and the integral term accumulates an error larger than the maximal value for the regulation variable (windup), thus the system overshoots and continues to increase as this accumulated error is unwound. This problem can be addressed by:

- Initializing the controller integral to a desired value
- Increasing the setpoint in a suitable ramp
- Disabling the integral function until the PV has entered the controllable region
- Limiting the time period over which the integral error is calculated
- Preventing the integral term from accumulating above or below pre-determined bounds

Overshooting from known disturbances

For example, a PID loop is used to control the temperature of an electric resistance furnace, the system has stabilized. Now the door is opened and something cold is put into the furnace the temperature drops below the setpoint. The integral function of the controller tends to compensate this error by introducing another error in the positive direction. This overshoot can be avoided by freezing of the integral function after the opening of the door for the time the control loop typically needs to reheat the furnace.

Replacing the integral function by a model based part

Often the time-response of the system is approximately known. Then it is an advantage to simulate this time-response with a model and to calculate some unknown parameter from the actual response of the system. If for instance the system is an electrical furnace the response of the difference between furnace temperature and ambient temperature to changes of the electrical power will be similar to that of a simple RC low-pass filter multiplied by an unknown proportional coefficient. The actual electrical power supplied to the furnace is delayed by a low-pass filter to simulate the response of the temperature of the furnace and then the actual temperature minus the ambient temperature is divided by this low-pass filtered electrical power. Then, the result is stabilized by another low-pass filter leading to an estimation of the proportional coefficient. With this estimation, it is possible to calculate the required electrical power by dividing the setpoint of the temperature minus the ambient temperature by this coefficient. The result can then be used instead of the integral function. This also achieves a control error of zero in the steady-state, but avoids integral windup and can give a significantly improved control action compared to an optimized PID controller. This type of controller does work properly in an open loop situation which causes integral windup with an integral function. This is an advantage if, for example, the heating of a furnace has to be reduced for some time because of the failure of a heating element, or if the controller is used as an advisory system to a human operator who may not switch it to closed-loop operation. It may also be useful if the controller is inside a branch of a complex control system that may be temporarily inactive.

PI controller

A PI Controller (proportional-integral controller) is a special case of the PID controller in which the derivative (D) of the error is not used.

The controller output is given by

$$K_P \Delta + K_I \int \Delta \, dt$$

where Δ is the error or deviation of actual measured value (PV) from the setpoint (SP).

$$\Delta = SP - PV.$$

A PI controller can be modelled easily in software such as <u>Simulink</u> using a "flow chart" box involving <u>Laplace</u> operators:

$$C = \frac{G(1 + \tau s)}{\tau s}$$

where

$$G = K_P = \text{proportional gain}$$
$$G/\tau = K_I = \text{integral gain}$$

Setting a value for G is often a trade off between decreasing overshoot and increasing settling time.

The lack of derivative action may make the system more steady in the steady state in the case of noisy data. This is because derivative action is more sensitive to higher-frequency terms in the inputs.

Without derivative action, a PI-controlled system is less responsive to real (non-noise) and relatively fast alterations in state and so the system will be slower to reach setpoint and slower to respond to perturbations than a well-tuned PID system may be.

Deadband

Many PID loops control a mechanical device (for example, a valve). Mechanical maintenance can be a major cost and wear leads to control degradation in the form of either <u>stiction</u> or a <u>deadband</u> in the mechanical response to an input signal. The rate of mechanical wear is mainly a function of how often a device is activated to make a change. Where wear is a significant concern, the PID loop may have an output <u>deadband</u> to reduce the frequency of activation of the output (valve). This is accomplished by modifying the controller to hold its output steady if the change would be small (within

the defined deadband range). The calculated output must leave the deadband before the actual output will change.

Setpoint step change

The proportional and derivative terms can produce excessive movement in the output when a system is subjected to an instantaneous step increase in the error, such as a large setpoint change. In the case of the derivative term, this is due to taking the derivative of the error, which is very large in the case of an instantaneous step change. As a result, some PID algorithms incorporate the following modifications:

Derivative of the process variable
In this case the PID controller measures the derivative of the measured process variable (PV), rather than the derivative of the error. This quantity is always continuous (i.e., never has a step change as a result of changed setpoint). For this technique to be effective, the derivative of the PV must have the opposite sign of the derivative of the error, in the case of negative feedback control.

Setpoint ramping
In this modification, the setpoint is gradually moved from its old value to a newly specified value using a linear or first order differential ramp function. This avoids the discontinuity present in a simple step change.

Setpoint weighting
Setpoint weighting uses different multipliers for the error depending on which element of the controller it is used in. The error in the integral term must be the true control error to avoid steady-state control errors. This affects the controller's setpoint response. These parameters do not affect the response to load disturbances and measurement noise.

Limitations of PID control

While PID controllers are applicable to many control problems, and often perform satisfactorily without any improvements or even tuning, they can perform poorly in some applications, and do not in general provide optimal control. The fundamental difficulty with PID control is that it is a feedback system, with constant parameters, and no direct knowledge of the process, and thus overall performance is reactive and a compromise – while PID control is the best controller with no model of the process,[2] better performance can be obtained by incorporating a model of the process.

The most significant improvement is to incorporate feed-forward control with knowledge about the system, and using the PID only to control error. Alternatively, PIDs can be modified in more minor ways, such as by changing the parameters (either gain scheduling in different use cases or adaptively modifying them based on performance), improving measurement (higher sampling rate, precision, and accuracy, and low-pass filtering if necessary), or cascading multiple PID controllers.

PID controllers, when used alone, can give poor performance when the PID loop gains must be reduced so that the control system does not overshoot, oscillate or hunt about the

control setpoint value. They also have difficulties in the presence of non-linearities, may trade-off regulation versus response time, do not react to changing process behavior (say, the process changes after it has warmed up), and have lag in responding to large disturbances.

Linearity

Another problem faced with PID controllers is that they are linear, and in particular symmetric. Thus, performance of PID controllers in non-linear systems (such as HVAC systems) is variable. For example, in temperature control, a common use case is active heating (via a heating element) but passive cooling (heating off, but no cooling), so overshoot can only be corrected slowly – it cannot be forced downward. In this case the PID should be tuned to be overdamped, to prevent or reduce overshoot, though this reduces performance (it increases settling time).

Noise in derivative

A problem with the derivative term is that small amounts of measurement or process noise can cause large amounts of change in the output. It is often helpful to filter the measurements with a low-pass filter in order to remove higher-frequency noise components. However, low-pass filtering and derivative control can cancel each other out, so reducing noise by instrumentation is a much better choice. Alternatively, a nonlinear median filter may be used, which improves the filtering efficiency and practical performance.[9] In some case, the differential band can be turned off in many systems with little loss of control. This is equivalent to using the PID controller as a PI controller.

Improvements

Feed-forward

The control system performance can be improved by combining the feedback (or closed-loop) control of a PID controller with feed-forward (or open-loop) control. Knowledge about the system (such as the desired acceleration and inertia) can be fed forward and combined with the PID output to improve the overall system performance. The feed-forward value alone can often provide the major portion of the controller output. The PID controller can be used primarily to respond to whatever difference or error remains between the set point (SP) and the actual value of the process variable (PV). Since the feed-forward output is not affected by the process feedback, it can never cause the control system to oscillate, thus improving the system response and stability.

For example, in most motion control systems, in order to accelerate a mechanical load under control, more force or torque is required from the prime mover, motor, or actuator. If a velocity loop PID controller is being used to control the speed of the load and command the force or torque being applied by the prime mover, then it is beneficial to take the instantaneous acceleration desired for the load, scale that value appropriately and add it to the output of the PID velocity loop controller. This means that whenever the

load is being accelerated or decelerated, a proportional amount of force is commanded from the prime mover regardless of the feedback value. The PID loop in this situation uses the feedback information to change the combined output to reduce the remaining difference between the process setpoint and the feedback value. Working together, the combined open-loop feed-forward controller and closed-loop PID controller can provide a more responsive, stable and reliable control system.

Other improvements

In addition to feed-forward, PID controllers are often enhanced through methods such as PID gain scheduling (changing parameters in different operating conditions), fuzzy logic or computational verb logic. Further practical application issues can arise from instrumentation connected to the controller. A high enough sampling rate, measurement precision, and measurement accuracy are required to achieve adequate control performance. Another new method for improvement of PID controller is to increase the degree of freedom by using fractional order. The order of the integrator and differentiator add increased flexibility to the controller.

Cascade control

One distinctive advantage of PID controllers is that two PID controllers can be used together to yield better dynamic performance. This is called cascaded PID control. In cascade control there are two PIDs arranged with one PID controlling the setpoint of another. A PID controller acts as outer loop controller, which controls the primary physical parameter, such as fluid level or velocity. The other controller acts as inner loop controller, which reads the output of outer loop controller as setpoint, usually controlling a more rapid changing parameter, flowrate or acceleration. It can be mathematically proven that the working frequency of the controller is increased and the time constant of the object is reduced by using cascaded PID controller.

Alternative nomenclature and PID forms

Ideal versus standard PID form

The form of the PID controller most often encountered in industry, and the one most relevant to tuning algorithms is the standard form. In this form the K_p gain is applied to the I_{out}, and D_{out} terms, yielding:

$$\text{MV(t)} = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau)\, d\tau + T_d \frac{d}{dt} e(t) \right)$$

where

T_i is the integral time
T_d is the derivative time

In this standard form, the parameters have a clear physical meaning. In particular, the inner summation produces a new single error value which is compensated for future and past errors. The addition of the proportional and derivative components effectively predicts the error value at T_d seconds (or samples) in the future, assuming that the loop control remains unchanged. The integral component adjusts the error value to compensate for the sum of all past errors, with the intention of completely eliminating them in T_i seconds (or samples). The resulting compensated single error value is scaled by the single gain K_p.

In the ideal parallel form, shown in the controller theory section

$$MV(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t)$$

the gain parameters are related to the parameters of the standard form through $K_i = \frac{K_p}{T_i}$ and $K_d = K_p T_d$. This parallel form, where the parameters are treated as simple gains, is the most general and flexible form. However, it is also the form where the parameters have the least physical interpretation and is generally reserved for theoretical treatment of the PID controller. The standard form, despite being slightly more complex mathematically, is more common in industry.

Basing derivative action on PV

In most commercial control systems, derivative action is based on PV rather than error. This is because the digitised version of the algorithm produces a large unwanted spike when the SP is changed. If the SP is constant then changes in PV will be the same as changes in error. Therefore this modification makes no difference to the way the controller responds to process disturbances.

$$MV(t) = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau)\, d\tau + T_d \frac{d}{dt} PV(t) \right)$$

Basing proportional action on PV

Most commercial control systems offer the option of also basing the proportional action on PV. This means that only the integral action responds to changes in SP. While at first this might seem to adversely affect the time that the process will take to respond to the change, the controller may be retuned to give almost the same response - largely by increasing K_p. The modification to the algorithm does not affect the way the controller responds to process disturbances, but the change in tuning has a beneficial effect. Often the magnitude and duration of the disturbance will be more than halved. Since most controllers have to deal frequently with process disturbances and relatively rarely with SP

changes, properly tuned the modified algorithm can dramatically improve process performance.

$$\text{MV(t)} = K_p \left(PV(t) + \frac{1}{T_i} \int_0^t e(\tau)\, d\tau + T_d \frac{d}{dt} PV(t) \right)$$

Tuning methods such as Ziegler-Nichols and Cohen-Coon will not be reliable when used with this algorithm. King[12] describes an effective chart-based method.

Laplace form of the PID controller

Sometimes it is useful to write the PID regulator in Laplace transform form:

$$G(s) = K_p + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s}$$

Having the PID controller written in Laplace form and having the transfer function of the controlled system makes it easy to determine the closed-loop transfer function of the system.

PID Pole Zero Cancellation

The PID equation can be written in this form:

$$G(s) = K_d \frac{s^2 + \frac{K_p}{K_d} s + \frac{K_i}{K_d}}{s}$$

When this form is used it is easy to determine the closed loop transfer function.

$$H(s) = \frac{1}{s^2 + 2\zeta\omega_0 s + \omega_0^2}$$

If

$$\frac{K_i}{K_d} = \omega_0^2$$
$$\frac{K_p}{K_d} = 2\zeta\omega_0$$

Then

$$G(s)H(s) = \frac{K_d}{s}$$

This can be very useful to remove unstable poles

Series/interacting form

Another representation of the PID controller is the series, or interacting form

$$G(s) = K_c \frac{(\tau_i s + 1)}{\tau_i s}(\tau_d s + 1)$$

where the parameters are related to the parameters of the standard form through

$$K_p = K_c \cdot \alpha, \; T_i = \tau_i \cdot \alpha, \text{ and}$$
$$T_d = \frac{\tau_d}{\alpha}$$

with

$$\alpha = 1 + \frac{\tau_d}{\tau_i}.$$

This form essentially consists of a PD and PI controller in series, and it made early (analog) controllers easier to build. When the controllers later became digital, many kept using the interacting form.

Discrete implementation

The analysis for designing a digital implementation of a PID controller in a Microcontroller (MCU) or FPGA device requires the standard form of the PID controller to be discretised. Approximations for first-order derivatives are made by backward finite differences. The integral term is discretised, with a sampling time Δt, as follows,

$$\int_0^{t_k} e(\tau) \, d\tau = \sum_{i=1}^{k} e(t_i)\Delta t$$

The derivative term is approximated as,

$$\frac{de(t_k)}{dt} = \frac{e(t_k) - e(t_{k-1})}{\Delta t}$$

Thus, a velocity algorithm for implementation of the discretised PID controller in a MCU is obtained by differentiating $u(t)$, using the numerical definitions of the first and second derivative and solving for $u(t_k)$ and finally obtaining:

$$u(t_k) = u(t_{k-1}) + K_p \left[\left(1 + \frac{\Delta t}{T_i} + \frac{T_d}{\Delta t} \right) e(t_k) + \left(-1 - \frac{2T_d}{\Delta t} \right) e(t_{k-1}) + \frac{T_d}{\Delta t} e(t_k}$$

H-infinity methods in control theory

H∞ (i.e. "H-infinity") methods are used in control theory to synthesize controllers achieving robust performance or stabilization. To use H∞ methods, a control designer expresses the control problem as a mathematical optimization problem and then finds the controller that solves this. H∞ techniques have the advantage over classical control techniques in that they are readily applicable to problems involving multivariable systems with cross-coupling between channels; disadvantages of H∞ techniques include the level of mathematical understanding needed to apply them successfully and the need for a reasonably good model of the system to be controlled. Problem formulation is important, since any controller synthesized will only be 'optimal' in the formulated sense: optimizing the wrong thing often makes things worse rather than better. Also, non-linear constraints such as saturation are generally not well-handled.

The term H∞ comes from the name of the mathematical space over which the optimization takes place: H∞ is the space of matrix-valued functions that are analytic and bounded in the open right-half of the complex plane defined by Re(s) > 0; the H∞ norm is the maximum singular value of the function over that space. (This can be interpreted as a maximum gain in any direction and at any frequency; for SISO systems, this is effectively the maximum magnitude of the frequency response.) H∞ techniques can be used to minimize the closed loop impact of a perturbation: depending on the problem formulation, the impact will either be measured in terms of stabilization or performance.

Simultaneously optimizing robust performance and robust stabilization is difficult. One method that comes close to achieving this is H∞ loop-shaping, which allows the control designer to apply classical loop-shaping concepts to the multivariable frequency response to get good robust performance, and then optimizes the response near the system bandwidth to achieve good robust stabilization.

Intelligent control is a class of control techniques that use various AI computing approaches like neural networks, Bayesian probability, fuzzy logic, machine learning, evolutionary computation and genetic algorithms.

Neural network controllers

Neural networks have been used to solve problems in almost all spheres of science and technology. Neural network control basically involves two steps:

- System identification
- Control

It has been shown that a feedforward network with nonlinear, continuous and differentiable activation functions have universal approximation capability. Recurrent

networks have also been used for system identification. Given, a set of input-output data pairs, system identification aims to form a mapping among these data pairs. Such a network is supposed to capture the dynamics of a system.

Bayesian controllers

Bayesian probability has produced a number of algorithms that are in common use in many advanced control systems, serving as state space estimators of some variables that are used in the controller.

The Kalman filter and the Particle filter are two examples of popular Bayesian control components. The Bayesian approach to controller design requires often an important effort in deriving the so-called system model and measurement model, which are the mathematical relationships linking the state variables to the sensor measurements available in the controlled system. In this respect, it is very closely linked to the system-theoretic approach to control design.

Process control

Process control is a statistics and engineering discipline that deals with architectures, mechanisms and algorithms for maintaining the output of a specific process within a desired range.

Process control is extensively used in industry and enables mass production of continuous processes such as oil refining, paper manufacturing, chemicals, power plants and many other industries. Process control enables automation, with which a small staff of operating personnel can operate a complex process from a central control room.

For example, heating up the temperature in a room is a process that has the specific, desired outcome to reach and maintain a defined temperature (e.g. 20°C), kept constant over time. Here, the temperature is the controlled variable. At the same time, it is the input variable since it is measured by a thermometer and used to decide whether to heat or not to heat. The desired temperature (20°C) is the setpoint. The state of the heater (e.g. the setting of the valve allowing hot water to flow through it) is called the manipulated variable since it is subject to control actions.

A commonly used control device called a programmable logic controller, or a PLC, is used to read a set of digital and analog inputs, apply a set of logic statements, and generate a set of analog and digital outputs. Using the example in the previous paragraph, the room temperature would be an input to the PLC. The logical statements would compare the setpoint to the input temperature and determine whether more or less heating was necessary to keep the temperature constant. A PLC output would then either open or close the hot water valve, an incremental amount, depending on whether more or less hot water was needed. Larger more complex systems can be controlled by a Distributed Control System (DCS) or SCADA system.

Types of control systems

In practice, process control systems can be characterized as one or more of the following forms:

- Discrete – Found in many manufacturing, motion and packaging applications. Robotic assembly, such as that found in automotive production, can be characterized as discrete process control. Most discrete manufacturing involves the production of discrete pieces of product, such as metal stamping.

- Batch – Some applications require that specific quantities of raw materials be combined in specific ways for particular durations to produce an intermediate or end result. One example is the production of adhesives and glues, which normally require the mixing of raw materials in a heated vessel for a period of time to form a quantity of end product. Other important examples are the production of food, beverages and medicine. Batch processes are generally used to produce a relatively low to intermediate quantity of product per year (a few pounds to millions of pounds).

- Continuous – Often, a physical system is represented through variables that are smooth and uninterrupted in time. The control of the water temperature in a heating jacket, for example, is an example of continuous process control. Some important continuous processes are the production of fuels, chemicals and plastics. Continuous processes in manufacturing are used to produce very large quantities of product per year (millions to billions of pounds).

Applications having elements of discrete, batch and continuous process control are often called hybrid applications.

Statistical process control

Statistical process control (SPC) is an effective method of monitoring a process through the use of control charts. Much of its power lies in the ability to monitor both the current center of a process and the process's variation about that center. By collecting data from samples at various points within the process, variations in the process that may affect the quality of the end product or service can be detected and corrected, thus reducing waste as well as the likelihood that problems will be passed on to the customer. It has an emphasis on early detection and prevention of problems.

Multivariable Process Control is a type of Statistical Process Control where a set of variables (manipulated variables and control variables) are identified and the joint variations within this set are captured by a step test. The Dynamics captured in the model curves are used to control the plant

Actuator; An actuator is a type of motor for moving or controlling a mechanism or system. It is operated by a source of energy, usually in the form of an electric current,

hydraulic fluid pressure or pneumatic pressure, and converts that energy into some kind of motion. An actuator is the mechanism by which an agent acts upon an environment. The agent can be either an artificial intelligence agent or any other autonomous being;

Automation. Automation is the use of control systems and information technologies to reduce the need for human work in the production of goods and services. In the scope of industrialization, automation is a step beyond mechanization.

Automatic control. Automatic control is the application of control theory for regulation of processes without direct human intervention. In the simplest type of an automatic control loop, a controller compares a measured value of a process with a desired set value, and processes the resulting error signal to change some input to the process, in such a way that the process stays at its set point despite disturbances. This closed-loop control is an application of negative feedback to a system.

Closed-loop controller. Control theory is an interdisciplinary branch of engineering and mathematics that deals with the behavior of dynamical systems. The external input of a system is called the reference. When one or more output variables of a system need to follow a certain reference over time, a controller manipulates the inputs to a system to obtain the desired effect on the output of the system.

The usual objective of a control theory is to calculate solutions for the proper corrective action from the controller that result in system stability, that is, the system will hold the set point and not oscillate around it.

The inputs and outputs of a continuous control system are generally related by nonlinear differential equations. A transfer function can sometimes be obtained by

1. Finding a solution of the nonlinear differential equations,
2. Linear zing the nonlinear differential equations at the resulting solution (i.e. trim point),
3. Finding the Laplace Transform of the resulting linear differential equations, and
4. Solving for the outputs in terms of the inputs in the Laplace domain.

The transfer function is also known as the system function or network function. The transfer function is a mathematical representation, in terms of spatial or temporal frequency, of the relation between the input and output of a linear time-invariant solution of the nonlinear differential equations describing the system.

Control panel. A control panel is a flat, often vertical, area where control or monitoring instruments are displayed.

They are found in factories to monitor and control machines or production lines and in places such as nuclear power plants, ships, aircraft and mainframe computers. Older

control panels are most often equipped with push buttons and analog instruments, whereas today in many cases touch screens are used for monitoring and control purposes

Control system. A control system is a device, or set of devices to manage, command, direct or regulate the behavior of other devices or system.

There are two common classes of control systems, with many variations and combinations: logic or sequential controls, and feedback or linear controls. There is also fuzzy logic, which attempts to combine some of the design simplicity of logic with the utility of linear control. Some devices or systems are inherently not controllable.

Control theory. Control theory is an interdisciplinary branch of engineering and mathematics that deals with the behavior of dynamical systems. The external input of a system is called the reference. When one or more output variables of a system need to follow a certain reference over time, a controller manipulates the inputs to a system to obtain the desired effect on the output of the system.

Controllability. Controllability is an important property of a control system, and the controllability property plays a crucial role in many control problems, such as stabilization of unstable systems by feedback, or optimal control.

Controllability and operability are dual aspects of the same problem.

Roughly, the concept of controllability denotes the ability to move a system around in its entire configuration space using only certain admissible manipulations. The exact definition varies slightly within the framework or the type of models applied.

Current loop.

Digital

For digital serial communications, a current loop is a communication interface that uses current instead of voltage for signaling. Current loops can be used over moderately long distances (tens of kilometers), and can be interfaced with optically isolated links.

Long before the RS-232 standard, current loops were used to send digital data in serial form for teleprompters. More than two teleprinters could be connected on a single circuit allowing a simple form of networking. Older teleprinters used a 60 mA current loop. Later machines, such as the Teletype Model 33, operated on a lower 20 mA current level and most early minicomputers featured a 20 mA current loop interface, with an RS-232 port generally available as a more expensive option. The original IBM PC serial port card had provisions for a 20 mA current loop. A digital current loop uses the absence of current for high (space or break), and the presence of current in the loop for low (mark).

The maximum resistance for a current loop is limited by the available voltage. Current loop interfaces usually use voltages much higher than those found on an RS-232 interface, and cannot be interconnected with voltage-type inputs without some form of level translator circuit.

MIDI (Musical Instrument Digital Interface) is a digital current loop interface.

Analog

Analog current loops are used where a device must be monitored or controlled remotely over a pair of conductors. Only one current level can be present at any time.

Given its analog nature, current loops are easier to understand and debug than more complicated digital field buses, requiring only a handheld digital millimeter in most situations. Using field buses and solving related problems usually requires much more education and understanding than required by simple current loop systems.

Additional digital communication to the device can be added to current loop using HART Protocol. Digital process buses such as FOUNDATION Field bus and Profibus may replace analog current loops.

Digital control. Digital control is a branch of control theory that uses digital computers to act as system controllers. Depending on the requirements, a digital control system can take the form of a microcontroller to an ASIC to a standard desktop computer. Since a digital computer is a discrete system, the Laplace transform is replaced with the Z-transform. Also since a digital computer has finite precision (See quantization), extra care is needed to ensure the error in coefficients, A/D conversion, D/A conversion, etc. are not producing undesired or unplanned effects.

Distributed control system. A distributed control system (DCS) refers to a control system usually of a manufacturing system process or any kind of dynamic system, in which the controller elements are not central in location (like the brain) but are distributed throughout the system with each component sub-system controlled by one or more controllers. The entire system of controllers is connected by networks for communication and monitoring.

Fieldbus. Fieldbus is the name of a family of industrial computer network protocols used for real-time distributed control, now standardized as IEC 61158.

A complex automated industrial system — such as manufacturing assembly line — usually needs an organized hierarchy of controller systems to function. In this hierarchy there is usually a Human Machine Interface (HMI) at the top, where an operator can monitor or operate the system. This is typically linked to a middle layer of programmable logic controllers (PLC) via a non-time-critical communications system (e.g. Ethernet). At

the bottom of the control chain is the fieldbus that links the PLCs to the components that actually do the work, such as sensors, actuators, electric motors, console lights, switches, valves and contactors.

Flow control valve. Electric flow control valve regulates the flow or pressure of a fluid. Control valves normally respond to signals generated by independent devices such as flow meters or temperature gauges.

Control valves are normally fitted with actuators and positioners. Pneumatically-actuated globe valves and Diaphragm Valves are widely used for control purposes in many industries, although quarter-turn types such as (modified) ball, gate and butterfly valves are also used.

Fuzzy control system. A fuzzy control system is a control system based on fuzzy logic—a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0 (true or false respectively). Fuzzy logic is widely used in machine control. The term itself inspires a certain skepticism, sounding equivalent to "half-baked logic" or "bogus logic", but the "fuzzy" part does not refer to a lack of rigour in the method, rather to the fact that the logic involved can deal with concepts that cannot be expressed as "true" or "false" but rather as "partially true". Although genetic algorithms and neural networks can perform just as well as fuzzy logic in many cases, fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller.

Intelligent control. Intelligent control is a class of control techniques that use various AI computing approaches like neural networks, Bayesian probability, fuzzy logic, machine learning, evolutionary computation and genetic algorithms.

Laplace transform. The Laplace transform is a widely used integral transform with many applications in physics and engineering. Denoted $\mathcal{L}\left\{f(t)\right\}$, it is a linear operator of a function f(t) with a real argument t (t ≥ 0) that transforms it to a function F(s) with a complex argument s. This transformation is essentially bijective for the majority of practical uses; the respective pairs of f(t) and F(s) are matched in tables. The Laplace transform has the useful property that many relationships and operations over the originals f(t) correspond to simpler relationships and operations over the images F(s). It is named after Pierre-Simon Laplace, who introduced the transform in his work on probability theory.

The Laplace transform is related to the Fourier transform, but whereas the Fourier transform expresses a function or signal as a series of modes of vibration (frequencies),

the Laplace transform resolves a function into its <u>moments</u>. Like the Fourier transform, the Laplace transform is used for solving differential and integral equations. In physics and engineering it is used for analysis of <u>linear time-invariant</u> <u>systems</u> such as <u>electrical circuits</u>, <u>harmonic oscillators</u>, <u>optical devices</u>, and mechanical systems. In such analyses, the Laplace transform is often interpreted as a transformation from the <u>time-domain</u>, in which inputs and outputs are functions of time, to the <u>frequency-domain</u>, where the same inputs and outputs are functions of <u>complex</u> <u>angular frequency</u>, in <u>radians</u> per unit time. Given a simple mathematical or functional description of an input or output to a system, the Laplace transform provides an alternative functional description that often simplifies the process of analyzing the behavior of the system, or in synthesizing a new system based on a set of specifications.

<u>Measurement instruments</u>. In the <u>physical sciences</u>, <u>quality assurance</u>, and <u>engineering</u>, <u>measurement</u> is the activity of obtaining and comparing <u>physical quantities</u> of real-world <u>objects</u> and <u>events</u>. Established standard objects and events are used as <u>units</u>, and the process of measurement gives a number relating the item under study and the referenced unit of measurement. Measuring instruments, and formal <u>test methods</u> which define the instrument's use, are the means by which these relations of numbers are obtained. All measuring instruments are subject to varying degrees of <u>instrument error</u> and <u>measurement uncertainty</u>.

<u>Model predictive control</u>. Model Predictive Control, or MPC, is an advanced method of <u>process control</u> that has been in use in the <u>process</u> industries such as <u>chemical plants</u> and <u>oil refineries</u> since the 1980s. Model predictive controllers rely on dynamic models of the process, most often linear <u>empirical</u> models obtained by <u>system identification</u>.

<u>Negative feedback</u>. Negative feedback occurs when information about a gap between the actual value and a reference value of a <u>system</u> <u>parameter</u> is used to reduce the gap. Changes that move a value away from the reference value are <u>attenuated</u>. If a system has overall a high degree of negative <u>feedback</u>, then the system will tend to be <u>stable</u>.

<u>Nonlinear control</u>. Nonlinear control is the area of <u>control engineering</u> specifically involved with systems that are <u>nonlinear</u>, <u>time-variant</u>, or both. Many well-established analysis and design techniques exist for <u>LTI systems</u> (e.g., <u>root-locus</u>, <u>Bode plot</u>, <u>Nyquist criterion</u>, <u>state-feedback</u>, <u>pole placement</u>); however, one or both of the controller and the system under control in a general <u>control system</u> may not be an LTI system, and so these methods cannot necessarily be applied directly.

<u>Open-loop controller</u>. An open-loop controller, also called a non-feedback controller, is a type of <u>controller</u> that computes its input into a system using only the current <u>state</u> and its <u>model</u> of the system.

A characteristic of the open-loop controller is that it does not use <u>feedback</u> to determine if its output has achieved the desired goal of the input. This means that the system does not

observe the output of the processes that it is controlling. Consequently, a true open-loop system can not engage in machine learning and also cannot correct any errors that it could make. It also may not compensate for disturbances in the system.

PID controller. A proportional–integral–derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems – a PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process control inputs.

The PID controller calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D. Heuristically, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, or the power supplied to a heating element.

In the absence of knowledge of the underlying process, a PID controller has historically been considered to be the best controller. By tuning the three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the setpoint and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability.

Some applications may require using only one or two actions to provide the appropriate system control. This is achieved by setting the other parameters to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are fairly common, since derivative action is sensitive to measurement noise, whereas the absence of an integral term may prevent the system from reaching its target value due to the control action.

Positive feedback. Positive feedback is a process in which the effects of a small disturbance on a system include an increase in the magnitude of the perturbation. That is, A produces more of B which in turn produces more of A. In contrast, a system that responds to a perturbation in a way that reduces its effect is said to exhibit negative feedback. These concepts were first recognized as broadly applicable by Norbert Wiener in his 1948 work on cybernetics.

Positive feedback tends to cause system instability. When there is more positive feedback than there are stabilizing tendencies, there will usually be exponential growth of any oscillations or divergences from equilibrium. System parameters will typically accelerate

towards extreme values, which may damage or destroy the system, or may end with the system 'latched' into a new stable state. Positive feedback may be controlled by signals in the system being filtered, damped or limited, or it can be cancelled or reduced by adding negative feedback.

Programmable Logic Controller. A programmable logic controller (PLC) or programmable controller is a digital computer used for automation of electromechanical processes, such as control of machinery on factory assembly lines, amusement rides, or light fixtures. PLCs are used in many industries and machines. Unlike general-purpose computers, the PLC is designed for multiple inputs and output arrangements, extended temperature ranges, immunity to electrical noise, and resistance to vibration and impact. Programs to control machine operation are typically stored in battery-backed-up or non-volatile memory. A PLC is an example of a hard real time system since output results must be produced in response to input conditions within a limited time, otherwise unintended operation will result. Functionality

The functionality of the PLC has evolved over the years to include sequential relay control, motion control, process control, distributed control systems and networking. The data handling, storage, processing power and communication capabilities of some modern PLCs are approximately equivalent to desktop computers. PLC-like programming combined with remote I/O hardware, allow a general-purpose desktop computer to overlap some PLCs in certain applications. Regarding the practicality of these desktop computer based logic controllers, it is important to note that they have not been generally accepted in heavy industry because the desktop computers run on less stable operating systems than do PLCs, and because the desktop computer hardware is typically not designed to the same levels of tolerance to temperature, humidity, vibration, and longevity as the processors used in PLCs. In addition to the hardware limitations of desktop based logic, operating systems such as Windows do not lend themselves to deterministic logic execution, with the result that the logic may not always respond to changes in logic state or input status with the extreme consistency in timing as is expected from PLCs. Still, such desktop logic applications find use in less critical situations, such as laboratory automation and use in small facilities where the application is less demanding and critical, because they are generally much less expensive than PLCs.

In more recent years, small products called PLRs (programmable logic relays), and also by similar names, have become more common and accepted. These are very much like PLCs, and are used in light industry where only a few points of I/O (i.e. a few signals coming in from the real world and a few going out) are involved, and low cost is desired. These small devices are typically made in a common physical size and shape by several manufacturers, and branded by the makers of larger PLCs to fill out their low end product range. Popular names include PICO Controller, NANO PLC, and other names implying very small controllers. Most of these have between 8 and 12 digital inputs, 4 and 8 digital

outputs, and up to 2 analog inputs. Size is usually about 4" wide, 3" high, and 3" deep. Most such devices include a tiny postage stamp sized LCD screen for viewing simplified ladder logic (only a very small portion of the program being visible at a given time) and status of I/O points, and typically these screens are accompanied by a 4-way rocker push-button plus four more separate push-buttons, similar to the key buttons on a VCR remote control, and used to navigate and edit the logic. Most have a small plug for connecting via RS-232 or RS-485 to a personal computer so that programmers can use simple Windows applications for programming instead of being forced to use the tiny LCD and push-button set for this purpose. Unlike regular PLCs that are usually modular and greatly expandable, the PLRs are usually not modular or expandable, but their price can be two orders of magnitude less than a PLC and they still offer robust design and deterministic execution of the logic.

PLC topics

Features

Control panel with PLC (grey elements in the center). The unit consists of separate elements, from left to right; power supply, controller, relay units for in- and output

The main difference from other computers is that PLCs are armored for severe conditions (such as dust, moisture, heat, cold) and have the facility for extensive input/output (I/O) arrangements. These connect the PLC to sensors and actuators. PLCs read limit switches, analog process variables (such as temperature and pressure), and the positions of complex positioning systems. Some use machine vision. On the actuator side, PLCs operate electric motors, pneumatic or hydraulic cylinders, magnetic relays, solenoids, or analog outputs. The input/output arrangements may be built into a simple PLC, or the PLC may have external I/O modules attached to a computer network that plugs into the PLC.

Scan time

A PLC program is generally executed repeatedly as long as the controlled system is running. The status of physical input points is copied to an area of memory accessible to the processor, sometimes called the "I/O Image Table". The program is then run from its first instruction rung down to the last rung. It takes some time for the processor of the PLC to evaluate all the rungs and update the I/O image table with the status of outputs. This scan time may be a few milliseconds for a small program or on a fast processor, but older PLCs running very large programs could take much longer (say, up to 100 ms) to execute the program. If the scan time was too long, the response of the PLC to process conditions would be too slow to be useful.

As PLCs became more advanced, methods were developed to change the sequence of ladder execution, and subroutines were implemented. This simplified programming and could also be used to save scan time for high-speed processes; for example, parts of the program used only for setting up the machine could be segregated from those parts required to operate at higher speed.

Special-purpose I/O modules, such as timer modules or counter modules, could be used where the scan time of the processor was too long to reliably pick up, for example, counting pulses and interpreting quadrature from a shaft encoder. The relatively slow PLC could still interpret the counted values to control a machine, but the accumulation of pulses was done by a dedicated module that was unaffected by the speed of the program execution.

System scale

A small PLC will have a fixed number of connections built in for inputs and outputs. Typically, expansions are available if the base model has insufficient I/O.

Modular PLCs have a chassis (also called a rack) into which are placed modules with different functions. The processor and selection of I/O modules are customized for the particular application. Several racks can be administered by a single processor, and may have thousands of inputs and outputs. A special high speed serial I/O link is used so that racks can be distributed away from the processor, reducing the wiring costs for large plants.

User interface

See also: User interface and List of human-computer interaction topics

PLCs may need to interact with people for the purpose of configuration, alarm reporting or everyday control. A human-machine interface (HMI) is employed for this purpose. HMIs are also referred to as man-machine interfaces (MMIs) and graphical user interface (GUIs). A simple system may use buttons and lights to interact with the user. Text displays are available as well as graphical touch screens. More complex systems use programming and monitoring software installed on a computer, with the PLC connected via a communication interface.

Communications

PLCs have built in communications ports, usually 9-pin RS-232, but optionally EIA-485 or Ethernet. Modbus, BACnet or DF1 is usually included as one of the communications protocols. Other options include various fieldbuses such as DeviceNet or Profibus. Other communications protocols that may be used are listed in the List of automation protocols.

Most modern PLCs can communicate over a network to some other system, such as a computer running a SCADA (Supervisory Control And Data Acquisition) system or web browser.

PLCs used in larger I/O systems may have peer-to-peer (P2P) communication between processors. This allows separate parts of a complex process to have individual control while allowing the subsystems to co-ordinate over the communication link. These

communication links are also often used for HMI devices such as keypads or PC-type workstations.

Programming

PLC programs are typically written in a special application on a personal computer, then downloaded by a direct-connection cable or over a network to the PLC. The program is stored in the PLC either in battery-backed-up RAM or some other non-volatile flash memory. Often, a single PLC can be programmed to replace thousands of relays.

Under the IEC 61131-3 standard, PLCs can be programmed using standards-based programming languages. A graphical programming notation called Sequential Function Charts is available on certain programmable controllers. Initially most PLCs utilized Ladder Logic Diagram Programming, a model which emulated electromechanical control panel devices (such as the contact and coils of relays) which PLCs replaced. This model remains common today.

IEC 61131-3 currently defines five programming languages for programmable control systems: function block diagram (FBD), ladder diagram (LD), structured text (ST; similar to the Pascal programming language), instruction list (IL; similar to assembly language) and sequential function chart (SFC). These techniques emphasize logical organization of operations.

While the fundamental concepts of PLC programming are common to all manufacturers, differences in I/O addressing, memory organization and instruction sets mean that PLC programs are never perfectly interchangeable between different makers. Even within the same product line of a single manufacturer, different models may not be directly compatible.

PLC compared with other control systems

PLCs are well adapted to a range of automation tasks. These are typically industrial processes in manufacturing where the cost of developing and maintaining the automation system is high relative to the total cost of the automation, and where changes to the system would be expected during its operational life. PLCs contain input and output devices compatible with industrial pilot devices and controls; little electrical design is required, and the design problem centers on expressing the desired sequence of operations. PLC applications are typically highly customized systems, so the cost of a packaged PLC is low compared to the cost of a specific custom-built controller design. On the other hand, in the case of mass-produced goods, customized control systems are economical. This is due to the lower cost of the components, which can be optimally chosen instead of a "generic" solution, and where the non-recurring engineering charges are spread over thousands or millions of units.

For high volume or very simple fixed automation tasks, different techniques are used. For example, a consumer dishwasher would be controlled by an electromechanical cam timer costing only a few dollars in production quantities.

A microcontroller-based design would be appropriate where hundreds or thousands of units will be produced and so the development cost (design of power supplies, input/output hardware and necessary testing and certification) can be spread over many sales, and where the end-user would not need to alter the control. Automotive applications are an example; millions of units are built each year, and very few end-users alter the programming of these controllers. However, some specialty vehicles such as transit buses economically use PLCs instead of custom-designed controls, because the volumes are low and the development cost would be uneconomical.

Very complex process control, such as used in the chemical industry, may require algorithms and performance beyond the capability of even high-performance PLCs. Very high-speed or precision controls may also require customized solutions; for example, aircraft flight controls. Single-board computers using semi-customized or fully proprietary hardware may be chosen for very demanding control applications where the high development and maintenance cost can be supported. "Soft PLCs" running on desktop-type computers can interface with industrial I/O hardware while executing programs within a version of commercial operating systems adapted for process control needs.

Programmable controllers are widely used in motion control, positioning control and torque control. Some manufacturers produce motion control units to be integrated with PLC so that G-code (involving a CNC machine) can be used to instruct machine movements.

PLCs may include logic for single-variable feedback analog control loop, a "proportional, integral, derivative" or "PID controller". A PID loop could be used to control the temperature of a manufacturing process, for example. Historically PLCs were usually configured with only a few analog control loops; where processes required hundreds or thousands of loops, a distributed control system (DCS) would instead be used. As PLCs have become more powerful, the boundary between DCS and PLC applications has become less distinct.

PLCs have similar functionality as Remote Terminal Units. An RTU, however, usually does not support control algorithms or control loops. As hardware rapidly becomes more powerful and cheaper, RTUs, PLCs and DCSs are increasingly beginning to overlap in responsibilities, and many vendors sell RTUs with PLC-like features and vice versa. The industry has standardized on the IEC 61131-3 functional block language for creating programs to run on RTUs and PLCs, although nearly all vendors also offer proprietary alternatives and associated development environments.

In recent years "Safety" PLCs have started to become popular, either as standalone models (Pilz PNOZ Multi, Sick etc.) or as functionality and safety-rated hardware added

to existing controller architectures (Allen Bradley Guardlogix, Siemens F-series etc.). These differ from conventional PLC types as being suitable for use in safety-critical applications for which PLCs have traditionally been supplemented with hard-wired safety relays. For example, a Safety PLC might be used to control access to a robot cell with trapped-key access, or perhaps to manage the shutdown response to an emergency stop on a conveyor production line. Such PLCs typically have a restricted regular instruction set augmented with safety-specific instructions designed to interface with emergency stops, light screens and so forth. The flexibility that such systems offer has resulted in rapid growth of demand for these controllers. Digital and analog signals

Digital or discrete signals behave as binary switches, yielding simply an On or Off signal (1 or 0, True or False, respectively). Push buttons, Limit switches, and photoelectric sensors are examples of devices providing a discrete signal. Discrete signals are sent using either voltage or current, where a specific range is designated as On and another as Off. For example, a PLC might use 24 V DC I/O, with values above 22 V DC representing On, values below 2VDC representing Off, and intermediate values undefined. Initially, PLCs had only discrete I/O.

Analog signals are like volume controls, with a range of values between zero and full-scale. These are typically interpreted as integer values (counts) by the PLC, with various ranges of accuracy depending on the device and the number of bits available to store the data. As PLCs typically use 16-bit signed binary processors, the integer values are limited between -32,768 and +32,767. Pressure, temperature, flow, and weight are often represented by analog signals. Analog signals can use voltage or current with a magnitude proportional to the value of the process signal. For example, an analog 0 - 10 V input or 4-20 mA would be converted into an integer value of 0 - 32767.

Current inputs are less sensitive to electrical noise (i.e. from welders or electric motor starts) than voltage inputs.

Regulator (automatic control). In automatic control, a regulator is a device which has the function of maintaining a designated characteristic. It performs the activity of managing or maintaining a range of values in a machine. The measurable property of a device is managed closely by specified conditions or an advance set value; or it can be a variable according to a predetermined arrangement scheme. It can be used generally to connote any set of various controls or devices for regulating or controlling items or objects.

SCADA. SCADA (supervisory control and data acquisition) generally refers to industrial control systems (ICS): computer systems that monitor and control industrial, infrastructure, or facility-based processes, as described below:

- Industrial processes include those of manufacturing, production, power generation, fabrication, and refining, and may run in continuous, batch, repetitive, or discrete modes.

- Infrastructure processes may be public or private, and include water treatment and distribution, wastewater collection and treatment, oil and gas pipelines, electrical power transmission and distribution, wind farms, civil defense siren systems, and large communication systems.
- Facility processes occur both in public facilities and private ones, including buildings, airports, ships, and space stations. They monitor and control HVAC, access, and energy

Servomechanism. A servomechanism, sometimes shortened to servo, is an automatic device that uses error-sensing negative feedback to correct the performance of a mechanism.

The term correctly applies only to systems where the feedback or error-correction signals help control mechanical position, speed or other parameters. For example, an automotive power window control is not a servomechanism, as there is no automatic feedback that controls position—the operator does this by observation. By contrast the car's cruise control uses closed loop feedback, which classifies it as a servomechanism.

Setpoint. Setpoint is the target value that an automatic control system, for example PID controller, will aim to reach. For example, a boiler control system might have a temperature setpoint that is a temperature the control system aims to attain.

Simatic S5 PLC. The Simatic S5 PLC is an automation system based on Programmable Logic Controllers. It was manufactured and sold by Siemens AG. Such automation systems control process equipment and machinery used in manufacturing. This product line is considered obsolete, as the manufacturer has since replaced it with their newer Simatic S7 PLC. However, the S5 PLC still has a huge installation base in factories around the world.

Sliding mode control. In control theory, sliding mode control, or SMC, is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to "slide" along a cross-section of the system's normal behavior. The state-feedback control law is not a continuous function of time. Instead, it can switch from one continuous structure to another based on the current position in the state space. Hence, sliding mode control is a variable structure control method. The multiple control structures are designed so that trajectories always move toward an adjacent region with a different control structure, and so the ultimate trajectory will not exist entirely within one control structure. Instead, it will slide along the boundaries of the control structures. The motion of the system as it slides along these boundaries is called a sliding mode and the geometrical locus consisting of the boundaries is called the sliding (hyper)surface. In the context of modern control theory, any variable structure system, like a system under SMC, may be viewed as a special case of a hybrid dynamical system as the system both flows through a continuous state space but also moves through different discrete control modes.

Temperature control. Temperature control is a process in which change of temperature of a space (and objects collectively there within) is measured or otherwise detected, and the passage of heat energy into or out of the space is adjusted to achieve a desired average temperature. Control loops;A home thermostat is an example of a closed control loop: It constantly assesses the current room temperature and controls a heater and/or air conditioner to increase or decrease the temperature according to user-defined setting(s). A simple (low-cost, cheap) thermostat merely switches the heater or air conditioner either on or off, and temporary overshoot and undershoot of the desired average temperature must be expected. A more expensive thermostat varies the amount of heat or cooling provided by the heater or cooler, depending on the difference between the required temperature (the "setpoint") and the actual temperature. This minimizes over/undershoot. The process is called PID and is implemented using a PID Controller.

Transducer. A transducer is a device that converts one form of energy to another. Energy types include (but are not limited to) electrical, mechanical, electromagnetic (including light), chemical, acoustic or thermal energy. While the term transducer commonly implies the use of a sensor/detector, any device which converts energy can be considered a transducer. Transducers are widely used in measuring instruments.

Process control monitoring. PCM is associated with designing and fabricating special structures that can monitor technology specific parameters such as Vth in CMOS and Vbe in Bipolars. These structures are placed across the wafer at specific locations along with the chip produced so that a closer look into the process variation is possible.